MANAGING SEDIMENTS AND NUTRIENTS IN THE SUSQUEHANNA RIVER BASIN

SUSQUEHANNA RIVER BASIN COMMISSION

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MANAGING SEDIMENTS AND NUTRIENTS IN THE SUSQUEHANNA RIVER BASIN

Final Report

BY

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SUSQUEHANNA RIVER BASIN COMMISSION

The Susquehanna River Basin Commission was created as an independent agency by a federal-interstate compact* among the states of Maryland, New York, Commonwealth of Pennsylvania, and the federal government. In creating the Commission, the Congress and state legislatures formally recognized the water resources of the Susquehanna River Basin as a regional asset vested with local, state, and national interests for which all the parties share responsibility. As the single federal-interstate water resources agency with basinwide authority, the Commission's goal is to effect coordinated planning, conservation, management, utilization, development and control of basin water resources among the government and private sectors.

*Statutory *Citations: Federal - Pub. L. 91-575, 84 Stat. 1509 (December 1970); Maryland - Natural Resources Sec. 8-301 (Michie 1974); New York - ECL Sec. 21-1301 (McKinney 1973); and Pennsylvania - 32 P.S. 820.1 (Supp. 1976).*

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INTRODUCTION

Among the most serious problems facing the Chesapeake Bay and its tributaries is an excess of the nutrients, nitrogen and phosphorus, caused by human activities on the land. To alleviate this problem the historic 1987 Chesapeake Bay Agreement set a goal to achieve "by the year 2000 at least a 40 percent reduction of nitrogen and phosphorus entering the main stem of the Chesapeake Bay." So stated the Chesapeake Executive Council in its Joint Tributary Strategy Statement (Directive No. 93-1). It goes on to note that the 1992 amendments to the Agreement called on their jurisdictions to develop tributary-specific nutrient reduction strategies.

The Commonwealth of Pennsylvania currently is developing such strategies for the Susquehanna and Potomac River basins. To meet the 40 percent reduction goals in the Susquehanna, nitrogen levels must be reduced by 18.3 million pounds, and phosphorus by 2.22 million pounds. Pennsylvania estimates that its existing four-part nonpoint source control program will achieve 89.1 percent of the nitrogen reduction and 62.6 percent of the phosphorus reduction required in the Susquehanna basin (Pa. DEP, 1994, p. 6). A number of options are being explored for closing the reduction shortfalls.

In the fall of 1993 the Pennsylvania Department of Environmental Protection (Pa. DEP) contracted with the Susquehanna River Basin Commission (SRBC) to undertake a study exploring additional options for achieving the reduction targets. The goal of this work is to find innovative means for reducing the loads of sediments and adsorbed nutrients passing down the river, through the three hydroelectric projects at its lower end, and into the bay.

In the sections that follow the magnitude of the problem is laid out, the logic for rejecting certain classes of options, and the case for accepting others is presented. Finally, the implications of the options chosen on Pennsylvania's ability to maintain the nutrient cap are discussed.

CURRENT KNOWLEDGE OF SEDIMENT AND NUTRIENT LOADS IN THE SUSQUEHANNA RIVER

Historical Perspective

The length of the data record measuring sediment loads carried by the river is relatively short. However, annual average rates of deposition can be inferred from periodic measurement of cross sections of reservoir bottoms, or from analysis of cores of bottom sediments. There seems to be general agreement that, at least within the present century, annual average loads coming down the Susquehanna are declining. Williams and Reed (1972) concluded that sediment discharge from the Juniata River basin declined 25 percent between 1951 and 1967. They speculated further that, based on reservoir-survey data of the Safe Harbor Dam impoundment made by Schuleen and Higgins (1953), annual sediment discharge in the middle and late 1930's in the main stem was three to four times its late 1960's level. They attribute much

of the apparent decline of the sediment load in the main stem Susquehanna to the decline of anthracite coal mining and processing in the region. Williams and Reed caution that the downward trend in sediment discharge may be offset in the future by the high sediment yields associated with urbanization.

Several studies document the flows, nutrient transport, and sediment deposition in the upper Chesapeake Bay, the roughly 112 miles (180 km) of the bay above the mouth of the Potomac River. Much of the earlier literature is summarized in a paper by Schubel and Pritchard (1986). (The page citations in the following paragraphs are to their paper.) They begin by defining the Chesapeake Bay estuarine system as made up of the *bay proper* and its *tributary estuaries* (p. 236). The Susquehanna River is identified as the only tributary that discharges directly into the main body of the bay (p. 236). The *upper Chesapeake Bay*, ("upper bay"), is defined as the region extending from the mouth of the Susquehanna at Havre de Grace, Maryland to a line extending across the bay just north of the mouth of the Potomac Estuary, a distance of approximately 112 miles (180 km) (p. 237).

The Susquehanna River is the source of 87 percent of the fresh water reaching the upper bay (p. 237). Typically, there is a high flow period in the spring (usually March or April, but sometimes as early as January and as late as May). Flows are low to moderate the remainder of the year, with secondary maxima often in the late fall or early winter. The average discharge varies widely from year to year, and at least three large floods have occurred since 1900 (p. 248-249).

Schubel and Pritchard, quoting a 1984 study, report that the Susquehanna River is the source of 61 percent of the *total bay sedimentation* (p. 242). Another study suggests that the proportion from the Susquehanna probably is much less. Hobbs and others (1992) present information about sediment deposited or eroded balanced against sediment sources in the Chesapeake Bay as an integrated whole (op cit., p. 292). Clearly, the Susquehanna River is a major source of *suspended sediment*, seconded only to shoreline erosion in Maryland (op cit., p. 295). In attempting to reconcile differences between potential sources and the quantity of sediment deposited, Hobbs and his associates identify at least three possibilities not included in their calculus: (1) suspended sediment from tributaries other than the Susquehanna; (2) bed load from all tributaries, including the Susquehanna; and, (3) sand brought in through the mouth of the bay from the continental shelf (op cit., p. 296).

Schubel and Pritchard report further, approximately 70 percent of the sediment input from the Susquehanna River is deposited in the upper 28 miles (45 km) of the bay. The remainder is carried farther seaward (p. 242-243). During years without major floods the annual suspended sediment load from the Susquehanna is an estimated 1.0 ± 0.33 million tons (0.9 ± 0.3 mill. metric tons). Over 50 percent of the input occurs during the few weeks of the spring freshet (p. 244).

Using sediment budget calculations, sediment deposition in the upper 28 mile reach was an estimated 0.6 cm per year. An alternative approach, based on the decay of Pb-210 provided an estimate of 0.45 cm per year for the same segment of the upper bay (p. 244).

Sedimentation in the upper bay is dominated by episodic high-flow events. Tropical Storm *Agnes* in June 1972 was the first such episode to be well documented by scientists. In one week an estimated 33 million tons (30 mill. metric tons) of suspended sediment was discharged by the Susquehanna River into the upper bay, an amount equivalent to the input of 30 average years. About 75 percent of it was deposited in the upper 28 miles of the bay, forming a deposit which averaged 20 cm in thickness (p. 246).

A related study that analyzed discharge data collected at Conowingo Dam concluded that between 1966 and 1976 the Susquehanna discharged 55 million tons of suspended sediment to the bay. About 44 million tons of that total was discharged during two floods: 33 million tons with the *Agnes* event, and 11 million tons with Hurricane *Eloise* in September 1975 (p. 246).

A study involving Pb-210 and Cs-137 dating of core samples from the extreme upper bay concluded that the Agnes event and the Great Flood of 1936 accounted for more than 50 percent of all sediment deposited in the upper bay since 1900. The same study estimated that the 1936 flood produced a deposit in the upper 28 mile reach about 36 cm thick (p. 246).

During the Agnes event, suspended sediment discharge at Conowingo (33 million tons) was four times that measured nearly 40 miles upstream at Harrisburg (8 million tons). Schubel and Pritchard state that resuspension of sediment deposits in the river and in the reservoirs, deposits that accumulate between flood events, is the only way to explain the difference (p. 346). One study estimates that when river flows are below 400,000 cfs (11,200 m^3 per second), at least half and usually two-thirds of sediment transported past Harrisburg does not pass Conowingo (p. 246). During major floods this material is scoured and moved to the bay. (Flows of the magnitude to produce scouring in Conowingo Pond, > 400,000 cfs, have a probability of 0.1 of occurring in any year [Fed. Emergency Management Agency, 1979, Table 1]). The result is to double the 56-year average river sediment discharge from 1.0 million tons in years of normal discharge to about 2.2 million tons per year. Schubel and Pritchard conclude: "The dams increase the amount of sediment discharged during floods and decrease the amount discharged during average and low-flow years" (p. 247).

The Susquehanna River is the primary source of nutrients in the upper bay. The river contributes more than 80 percent of total nitrogen and 65 percent of total phosphorus from all riverine sources to that area (p. 247). Probably 50 to 60 percent of the Susquehanna's annual input of nitrate to the upper bay occurs during the spring freshet (Ibid.). Much of it passes through that portion of the bay without being assimilated because of short residence times relative to the slow uptake rates by plankton during this season (Ibid.). Nitrate concentrations decline during the late spring and summer. In the summer and fall point sources of nitrate become the main input of nitrogen to the upper bay (Ibid.).

Phosphorus, primarily in the form of phosphate, is distributed much more uniformly in the upper bay. During the summer more than half of the total phosphorus is present as dissolved organic phosphate. Point sources account for 61 percent of the total phosphorus input to the system (p. 247).

Summing up nutrient conditions in the upper bay, Schubel and Pritchard state:

> Enrichment problems in the upper bay are most significant in summer when water-residence time is increased, light availability and temperature are increased, and vertical stability is high. Nutrient levels and primary production in the main body of the upper bay have increased over the past several decades, and the increases are associated primarily with increased inputs of nutrients by the Susquehanna River (p. 247).

Periodic bathymetric surveys of reservoirs can provide insights into changes occurring over time in the configuration of the reservoir bottom. However, a question exists as to how finely such techniques can resolve changes in bottom topography. For example, Gross and others (1978) note that if Tropical Storm Agnes scoured 24 million tons (22 million metric tons) of sediment from the three lower Susquehanna reservoirs, the entire amount could have been derived from eroding 1.5 feet (0.5 meter) of the bottom. Biggs and Howell (1984, p. 111) report most researchers assume an error estimate of 0.3 m for two soundings from the same location in depths less than 20 m. One study of the southern Chesapeake reported the 95 percent confidence interval between co-located individual depths, on separate surveys, is ± 1.1 m. If error terms are generally of this magnitude, major problems exist with using bathymetry to measure the time rate of sediment accumulation, because the error is of the same magnitude as the expected average sedimentation rate.

Recent Investigations

<u>SRBC Monitoring Results</u>

Susquehanna River Basin Commission staff estimated annual loads and yields of nutrients and suspended sediment produced by the Susquehanna River and ten of its tributaries for the period 1985 to 1989 (Ott and others, 1991). The calculated annual loads and yields varied from year-to-year. The variations were highly correlated with the annual water discharge. The results confirm the findings of other investigators that the highest nutrient yields come from the lower portion of the Susquehanna basin. These results have been aggregated to establish annual baseline values based on the 1985-89 monitoring period:

Total Nitrogen	150 million pounds
Total Phosphorus	8.7 million pounds
Suspended sediment	6,180 million pounds

(Ibid., p.155)

Note that these quantities represent the amounts reaching the lower end of the river and include any materials trapped in the reservoirs. The estimate of suspended sediment agrees well with the 6,000 million pound estimate reported by Williams and Reed (1972). Lang (1982) reported a suspended sediment load of 4,600 million pounds at Harrisburg. If the sediment from the tributaries and other areas below Harrisburg is factored in, as was done in the SRBC study, Lang's estimate would be on the order of 6,800 million pounds.

The sampling efforts continue at five sites in the basin in order to build a long-term data base. Data for 1990 to 1991 have been published by Takita and Edwards (1993). Total nitrogen, total phosphorus and suspended-sediment loads measured during calendar years 1990 and 1991 are compared with the 1985-89 baseline.

As explained previously, large quantities of the suspended sediment and total phosphorus loads are thought to be trapped in the reservoirs of three hydroelectric dams on the lower Susquehanna. Estimates of the quantities of nutrients and suspended sediment *passing* Conowingo Dam were derived in an identical way to those for the Susquehanna basin, using sampling data obtained by staff from the Towson, Maryland office of USGS. With these two data sets, one can estimate the quantity of material trapped in the reservoirs as follows:

Annual load entering the reservoirs *less* annual load passing Conowingo Dam *equals* annual load trapped in the reservoirs

The SRBC study gives the following estimates:

	Total Nitrogen	Total Phosphorus	Suspended Sediment
	Millions of pounds per year		
Total from Basin	150	8.70	6,180
Conowingo's output to Bay	147	5.13	1,780
Trapped in reservoirs	3	3.57	4,400

(Ott and others, 1991, Table 64, p.155)

These data suggest trap efficiencies, that is, percentage of inflows retained in reservoirs, of 2 percent for nitrogen, 41 percent for phosphorus, and 71 percent for sediment. In this connection the Academy of Natural Sciences of Philadelphia (Academy) calls attention to the wide range --- -192 percent to +78 percent --- reported in the literature for trap efficiencies in the lower Susquehanna reservoirs (1994, Table 2, p. 6). More will said about this later.

U.S. Geological Survey Study

Staff from the Lemoyne, Pa. district office of USGS collected data in 1990 to assess the quantity and quality of sediment in the reservoirs formed by the three hydroelectric dams in the lower Susquehanna (Hainly and others, 1995, p. 1). Historical reservoir bed elevations were compared with comparable data obtained during the study in order to estimate the amount of sediment storage remaining in the reservoirs (Ibid.). The study concludes:

> Lake Aldred [Holtwood Reservoir] and Lake Clarke [Safe Harbor Reservoir] reached equilibrium with incoming river sediment by 1910 and 1950, respectively, and are no longer storing sediment. Historical inflow and outflow data indicate that the reservoirs scour when the flow of the Susquehanna River at Conowingo, Md. exceeds 400,000 ft^3/s. The original capacity (in 1928) of the reservoir formed by Conowingo Dam was about 300,000 acre-ft. By 1959, deposition of sediment reduced the capacity to 235,000 acre-ft and by 1990, the capacity was only 196,000 acre-ft. A comparison of the cross-sectional data from Lake Aldred and Lake Clarke with those of Conowingo Reservoir indicates that the Conowingo Reservoir will probably reach equilibrium in the next 20 or 30 years. As the reservoirs fill, the percentage of sediment, nitrogen, phosphorus, and metals transported by the Susquehanna River that is deposited in the reservoirs will decrease, and the percentage that reaches the Chesapeake Bay will increase (op. cit., p. 37).

A copy of the USGS study is attached as Appendix A to the present report.

Maryland Department of Natural Resources Survey

Personnel from the Maryland Department of Natural Resources, collaborating with scientists from the Oak Ridge National Laboratory and a consulting firm, estimated sediment accretion rates in the Conowingo Reservoir by measuring levels of various radionuclides from deep cores of the reservoir bottom (McLean and others, 1991). These researchers estimate that net sediment deposition in the lower half *of the reservoir* ranges between 2 and 7 cm per year. Average sediment retention ranges between 0.44 and 1.65 million tons (0.4 and 1.5 million metric tons) per year, or 8 to 23 percent of the average annual sediment input to the reservoir reported from 1966 to 1976 (op. cit.. p.155). This period included two major storms that accounted for 90 percent of the sediment discharged through Conowingo Dam. In the absence of any storm events, a hypothetical situation, the authors estimate that the reservoir would retain 33-66 percent of the incoming sediment load. Thus, the occurrence of intense storm events has the effect of reducing long-term sediment retention in the reservoir by a factor of 3 to 4 (Ibid.).

Spring High Flows of 1993 and 1994

Spring rainstorms and snow melt from the March blizzard of 1993 led to the largest freshwater inflow to the Chesapeake Bay ever recorded (Zynjuk, 1994). The loads of nitrogen and phosphorus that spring were twice as high as the 1977-1992 average for the season, and suspended sediment was four times the spring average. In an "average" year about half of the nutrient and sediment loads entering the bay from the Susquehanna are transported during the spring. In 1993, approximately 60 percent of the annual nitrogen load, 74 percent of the phosphorus load, and 90 percent of the annual suspended sediment load was carried to the bay during the spring season (Ibid.).

River flows were well above normal in spring 1994 also. While the peak flow was about 80 percent that observed in 1993, total flow to the bay during the period January through July

was only slightly below 1993 levels (Blankenship, 1994). Sediment and nutrient loads to the bay during the 1994 freshet are not yet available; however, they should be well above normal. The extended period of high fresh water flows to the bay depressed salinity levels through July, resulting in above normal oyster mortalities (Ibid.).

LONG TERM IMPLICATIONS OF SEDIMENT AND NUTRIENT LOADS

Nutrient Caps

The 1987 Chesapeake Bay Agreement set the goal of achieving at least a 40 percent reduction of nitrogen and phosphorus entering the Chesapeake Bay by the year 2000. In the 1992 amendments to the Bay Agreement, the Chesapeake Executive Council pledged that the nutrient reduction strategies developed for each bay tributary would include a permanent cap on nutrient inputs (CEC, Directive No. 93-1). The year 2000 caps for the Pennsylvania portion of the Susquehanna are:

Nitrogen:	98.057 millions of pounds per year
Phosphorus	3.700 millions of pounds per year

(W. Matuszeski, 1995))

The EPA Chesapeake Bay Program has developed a Watershed Model (WSM) to estimate nutrient loadings to the Bay, and to evaluate the impacts of agricultural BMPs (Donigian and others, 1994, p.1). Refinement of and additions to the model's capabilities, data updates, and other improvements are an ongoing process for the WSM. A sediment transport simulation was added in Phase II of the model to handle sediment-nutrient processes (op cit., p. 157). However, neither the suspended sediment nor the nutrient simulations for the monitoring site below Conowingo Dam agreed very well with observed data. The Phase II report calls for improved modeling of the processes occurring within the reservoirs (op cit., p. 209 and 219). Both Phase III (currently underway) and Phase IV (scheduled for completion by 1996) of the WSM refinements include efforts to improve the reservoir simulation.

The tributary allocations ('caps') were derived from the results of various scenarios generated by the watershed model. It is important to the present discussion to know if the simulations assume that any of the nutrients passing through the Conowingo Pond are deposited there. That appears to be the case. Donigian and others (1994, Sec. 5.0) describe the sediment transport module of the HSPF ("Hydrologic Simulation Program-FORTRAN") model used in Phase II. They state:

> A major focus of Phase II was to include a more detailed representation of instream nutrient processes, particularly with respect to sediment-nutrient interactions...[t]he Phase II effort included significant modifications to the nutrient simulation routines in HSPF to allow inorganic N (ammonium) and P (orthophosphate) to adsorb to sediment and undergo settling, resuspension, and transport. (op cit., p. 151)

These authors conclude that, based on comparison of sediment loads simulated by the model with observed daily sediment concentration data at selected locations, "...the sediment results are adequate, but could be improved with further calibration." (op cit., p. 209)

The caps are specific quantities of nutrients, expressed as annual amounts passing the fall line, that all the parties to the Chesapeake Bay agreement accepted. Implicit in the agreement is the idea that load reduction efforts must increase over time to offset any increase in the nutrient loads reaching the bay. Given that the caps were derived by a process that assumes a portion of the nutrients transported down the Susquehanna are trapped in Conowingo Pond, then attention must be paid to the implications of the cessation of such trapping.

After Equilibrium

The ultimate destiny of all reservoirs is to be filled with sediment. So state Professor Ray Linsley and his co-authors in their well-known textbook (1992, p. 199). The precise meaning of "full" should be understood. It does **not** imply that all the water in the reservoir has been displaced by soil. (That undoubtedly is the ultimate fate of reservoirs, with the passage of sufficient time. This concept is analogous to the process of *lake succession* described by limnologists. [see, e.g., Goldman and Horne, 1983, p.350.]) Rather, an equilibrium is established between sediment inflows and outflows, such that within the normal range of flows, net deposition within the reservoir approaches zero. Such an equilibrium may be viewed as the steady-state sediment-storage capacity of a reservoir.

The role of the reservoirs on the sediment and nutrient discharges reaching the bay has been described in the report by the Academy of Natural Sciences (1994, p. 11). (A copy of this report is appended to the present report as Appendix B.) It sums up the situation as follows:

> The basic point is that, under steady-state conditions, the reservoirs will simply have no effect on the ultimate fate of sediment transported by the Susquehanna. Over time-intervals of sufficient length, there will be no net retention of sediment between Columbia, Pennsylvania, and Conowingo, Maryland, *just as if the reservoirs were not present* (emphasis supplied). The reservoirs will, however, continue to alter the timing of sediment delivery to the Bay, with more being delivered during major floods and less during the ensuing non-flood periods. Thus, the reservoirs will have no effect on long-term average delivery but will increase the variance about that average.

Nevertheless, the base loads estimates of nutrient and sediments for the fall line were derived from data for the period 1984-1987, not the 'long-term average.' More importantly, the base quantities were determined when sediment and phosphorus (and a small fraction of the nitrogen) were still being trapped in Conowingo Pond, that is, before "equilibrium." Therefore, once a quasi-steady state is achieved, the quantities reaching the bay will increase by the amount previously trapped. This fact has important ramifications for Pennsylvania's efforts to maintain the cap.

The magnitude of 'after-equilibrium' quantities going to the bay can only be roughly approximated from some of the findings mentioned earlier. The primary source of difficulty, as pointed out by Gross and others (1978) as well as in the Academy's report (1994), is the lack of any evaluation of the magnitude of errors associated with the sediment discharge estimates. The Academy notes, "In the absence of valid statistical confidence intervals, there is simply no objective way to assess how close any of the estimates of trap efficiency is likely to be to the true value for a given year or to the long-term average" (Ibid.).

Gross and colleagues, (1978, p. 107), in assessing sediment yields in a period that included two flood events as well as the end of a drought (1966-1976), make the judgment that trapping efficiencies in Conowingo Pond when peak daily flows are 400,000 cfs or less, range between 50 and 67 percent. If these values are assumed to reflect the normal range of trapping efficiencies at sub-flood flows, they can be used to place limits on the estimates of additional sediment that will reach the upper Chesapeake Bay after an equilibrium is reached.

Ott and his colleagues adjusted their 1985-89 data to the long-term average flows to generate what they term the baseline loads. The baseline value for suspended sediment coming from the Susquehanna basin is estimated as 6,180 millions of pounds per year (Ott and others, 1991, Table 64). The 50 percent and 67 percent bounds for this quantity are 3,090 and 4,141 million pounds, respectively. The SRBC monitoring report, making the same adjustment to the USGS-Towson data of outflows from Conowingo Pond, estimates the baseline quantity of trapped sediment to be 4,400 millions of pounds per year, or a trapping efficiency of 71 percent (Ibid.).

The Academy suggests that both the SRBC report and the USGS study overestimate the true mean trapping efficiency, because their analyses do not encompass years with major flows, during which sediment output from the reservoirs greatly exceeds input (1994, p. 7). As mentioned earlier, the authors of the Academy report go on to point out that the post-equilibrium condition is not a true steady state. Rather, the pulses of sediment and nutrients stored in the reservoirs to the bay will be larger during flood flows than would be the case in the absence of reservoirs. Following such a flood, the discharge of materials from the reservoirs decreases as net deposition replaces the scoured materials (op cit., p. 10-11). Taken all together, the result is great difficulty in trying to quantify the increased load to the Bay after "equilibrium" is reached. The Academy states, "In the long term, sediment dynamics in the reservoir system will comprise periods of gradual accumulation, punctuated by episodic flood-driven scouring. The timing and magnitude of these scouring events cannot be predicted with any certainty, because both are stochastic phenomena" (Ibid.).

Estimates of nutrient transport are even less reliable. A large portion of phosphorus is transported as particulate material--Ott and others suggest approximately 70 percent is in that form (1991, Table 43). Their data for 1985-89 indicate that about 40 percent is trapped (op cit., Table 64). The estimates of nutrients trapped are subject to all the limitations mentioned above in connection with estimating sediment trapping. Moreover, the Academy report points out that the principles governing the transport of fine particulates are poorly understood, citing that as a

central reason for our limited ability to accurately predict particle-bound contaminates in the Great Lakes (1994, p. 10).

The work of McLean and others (1991) discussed earlier is relevant here. Their findings relate to the movement of finer sediment particles, as measured by adsorbed radionuclides. Particle-bound nutrients tend to be transported by similar sized fractions of the suspended sediment load (Academy, 1994, p. 9). McLean and associates describe a highly dynamic system of sediment on or near the surface of the reservoir bottom. While they acknowledge net deposition of sediment occurs in the lower reaches of Conowingo Pond, they suggest a relatively high turnover rate of the deposited material. Overall, they estimate "...that 75 percent of the sediment load (and particle-associated contaminants) introduced into the reservoir ultimately reaches the Chesapeake Bay" (op cit., 1991, p. 156).

Implementation of Additional BMPs

One means of offsetting an increase in the nutrient and sediment loads that reach the bay involves the introduction of new, improved, or additional nonpoint-source best management practices (BMPs) at the source areas of the problem. This approach envisions multiple ways of achieving the most effective program: increased use of existing practices through additional technical assistance and cost-sharing efforts; adaptation of new (to the region) BMPs; targeting of BMPs to highly erosive areas; and improved enforcement of existing regulations. Given that the impacts of newly implemented BMPs do not show up as decreased loads at the fall line for several years, conceivably the (currently unquantifiable) increase in loads above the cap can be at least partially offset by vigorous additional efforts over the next ten to twenty years. Some of the possible ways of doing this are discussed later.

LOAD REDUCTION OPTIONS

Reservoir Management

Several means of reducing sediment accumulation in reservoirs have been tried. Sluice gates at different depths may pass finer sediments before they settle out. At times the sediment-laden inflow to a reservoir moves through the pool as a density current. Venting such currents through the sluiceways can reduce the trap efficiency by 2 to 10 percent.

Physical removal of sediment deposits is sometimes attempted. Flushing through sluice gates is possible, but its effectiveness seldom extends very far upstream. Siphoning or dredging of bottom sediments are other possibilities (Collar and Guzmán-Ríos, 1991, p. 15-23:15-24).

Alternatively, fixing/stabilizing contaminated sediments *in situ* has been used. This approach is currently under study by the Canadian environmental agency (SEDTEC, 1994).

The technical feasibility, financial reasonableness, and environmental acceptability of the several options are discussed in the following sections.

Dredging

1. Technical feasibility: The cutterhead dredge "...is probably the most well-known dredging vessel as well as the most efficient and versatile" (Herbich, p. 4.18). Portable cutterhead models with discharge pipes ranging in diameter from 8 inches to 20 inches and larger have been developed in the past several years. Rated output for these units range from 50 to 100 cubic yards per hour for 8-inch units up to 300 to 1500 yd^3/hr for 20-inch units, depending on the length of discharge pipe (op cit., Figure 4.46, p. 4.37). Assuming a discharge pipe of up to 8,000 feet would be needed to dredge Conowingo Pond at its widest point, and a length half that will be the "average" need, Figure 4.46 indicates that with a 20-inch dredge, productivity will be on the order of 350 to 500 yd^3/hour.

Based on the findings of the SRBC study, on average, 4,400 million pounds of sediment are trapped in the Conowingo, Holtwood and Safe Harbor Reservoirs annually (Ott and others, 1991, p.155). Assuming a density of dry sediment of 70 pounds per cubic foot, the *volume* of the sediment trapped annually is on the order of 2.3 million cubic yards. 4,600 to 6,600 hours of dredging at the rates specified above would be needed each year just to keep up with average annual deposition. These number of hours convert to working round the clock for 190 to 275 days per year.

Another way of viewing the magnitude of the annual dredging operation is to consider the quantity of dredged material to be disposed of each day. Using a 100-ton capacity railroad hopper car as the unit of measurement, 80 rail cars would be filled each work day at the 350 yd^3/hour rate; 116 cars per day at the 500 yd^3/hour rate.

However one looks at the quantities involved, the magnitude of the task is formidable. The scenario sketched out above does nothing whatever to reduce the load of sediment and nutrients already collected in the reservoirs. To consider removing substantial amounts of the existing sediment/nutrient load requires resources well beyond present technological capabilities. The USGS estimates that total sediment deposition in the three reservoirs is on the order of 260 million tons (Hainly and others, 1995, Table 4). If this estimate is accepted as reasonable, a 25-year effort to remove the accumulated materials would require nearly five times the resources of the annual deposition case. In other words, an additional 375 to 535 rail cars would need to be filled each work day. We submit that a work effort of this magnitude technically is not feasible to carry out in the constricted area around the reservoirs.

2. Financial Reasonableness: Costs associated with dredging are highly site specific. Additionally, they vary considerably among the type of dredge equipment used. Herbich presents the results of an economic analysis that relates type of dredge used to the distance the dredged material must be transported to a disposal site (1992, p. 8.53-8.56). This study of *navigational channel* dredging considered both offshore and upland disposal sites as distant as 70 miles. Type of dredge and transport system changed as distance increased, with unit costs ranging from about $10 per cubic yard to over $200 per cubic yard. Herbich characterizes these estimates as "..sufficiently accurate for the purpose of strategic comparisons, but do not necessarily reflect market prices" (Ibid., p. 8-54). All of the equipment analyzed was larger than that suitable for use in reservoirs of the size considered in the present study. Unit costs for the

smallest dredges considered and transport distances less than two miles were approximately $20 per cubic yard.

As a working value for the present analysis, in the absence of specific information, we will assume that the unit cost of operating a 20-inch cutterhead dredge is $12 per cubic yard. Based on the annual average deposition of 2.3 million cubic yards noted previously, the cost of just keeping up with the new sediment deposits would be on the order of $28 million per year.

3. <u>Environmental Acceptability</u>: Dredging can have negative impacts on the area from which the material is being removed. Bottom sediments may be contaminated with many potentially toxic chemicals. Generally such substances are associated with the finer-grained fraction of sediments that are most susceptible to dispersion (Herbich, 1992, p. 9.5). Dispersion of dredged material is a function of type of dredge used, dredging method, and type of sediment (Ibid.). Dispersion of finer sediments are of concern because of the resulting increased turbidity. Potentially, dredging can have negative environmental impacts on both the water column and the bottom sediments.

Environmental concerns about dredging extend beyond impacts at the dredge site to the matter of disposal of the spoil. A complex of federal environmental protection legislation surrounds the permitting of both dredging and disposal of dredged materials. The three primary federal laws governing dredging and disposal in navigable waters are: the National Environmental Policy Act of 1969 (NEPA), the Clean Water Act of 1977 (CWA), and the Marine Protection, Research, and Sanctuaries Act of 1972, (Herbich, 1991, p. 9.1). The first two are of special relevance to our discussion. NEPA's primary purpose is to assure that sufficient environmental and alternative project information is available to both federal agencies and the general public on issues that could have significant impact on the public (Ibid.). CWA's purpose is to restore and maintain the chemical, physical, and biological integrity of the waters of the United States. Section 404 of the CWA establishes criteria for the discharge of dredge or fill material into the nation's waters (Ibid., p. 9.2). Much of the material that follows comes from an extended conversation with Tom Filip, Assistant Chief, Regulatory Branch, Operations Division, Baltimore District, Corps of Engineers (Oral communication, September 28, 1994).

Any consideration of dredging large quantities of sediment from the reservoirs must confront the need for large disposal site(s). We concluded above that dredging the estimated 260 million cubic yards of material in the reservoir is not technically feasible. By way of comparison, we note that this quantity is about four times the capacity of the Hart-Miller disposal site for Baltimore Harbor dredging.

A proposal of such magnitude, involving as it does, federal licenses and actions that significantly affect the quality of the human environment, has NEPA impacts and, thus, invokes the need for an Environmental Impact Statement (EIS). Given the need for an EIS, the first compliance action under Section 404 is a *purpose and need analysis* (PNA).

The PNA defines the purpose of the proposed project, e.g., "remove deposited sediments from the reservoirs," and the need, e.g., "increase the efficiency of reservoirs." The next step

involves a risk assessment in which the consequences (positive and negative) of the entire menu of possible actions are considered. The first alternative involves consideration of the consequences of not carrying out the project--the *no action* option. Investigation of this alternative may reveal such dire long term consequences, that some response is forced, essentially without regard to cost.

If the consequences of no action are not large, continue the PNA: specify the need, and identify all ways conceivable of achieving the need. If dredging options are considered, a *bulk sediment analysis* is required. This involves testing for the presence of contaminants of concern, i.e., those on the EPA 307 toxics list.

By proceeding through the sampling and testing cycle, one is compiling the data for an iterative procedure in which one goes back to the list of processes for inclusion/exclusion of some of them. The end result is a dredging plan that explicitly identifies the public consequences of a particular action (or inaction).

Assuming that an acceptable dredging plan can be crafted, there remains the need for a parallel development of a plan for disposal of dredged material. Answers must be found to the questions 'Which reservoirs to dredge?', 'In what order?', 'In what quantity?' More importantly, an analysis of alternatives will be needed to quantify the environmental impacts at each proposed disposal site. The major issues to be confronted here are 'What's in the sediments?' and 'Where to dispose of the megavolumes of spoil materials?'

If the disposal sites encompass streams or wetlands, permits will be required. Before the permits can be issued, extensive testing must be done. All-in-all, the environmental regulatory process associated with any plan to dredge large quantities of sediment from the lower Susquehanna reservoirs is complex, lengthy (multi-year), and with little assurance that in the end it will be allowed.

Flushing and Siphoning Techniques

Several means of sediment mitigation through partially restoring lost reservoir capacity or minimizing future capacity reductions have been discussed by Collar and Guzmán-Ríos (1991, p. 15-21 to 15-24). The first of these involves flushing high-sediment load storm flows over the spillway. This procedure retards the rate of sedimentation in the reservoir but does not regain any capacity already lost. The next option involves flushing sediments through low-level outlets in the dam. The authors cite a UNESCO study that concluded this is the most effective means for partially restoring lost capacity. In the context of the present investigation, the intakes of the turbine units can function as low-level outlets. However, in discussing this matter with staff from the utilities it was learned that at flows that scour the bottom sediments, (approximately > 400,000 cfs), the river flow is also going over the spillway (O'Donel, Oral comm., Nov. 9, 1994). This is one of the conditions identified as part of the problem to be remedied, namely, flushing large 'slugs' of sediment and nutrients into the upper bay at times of high flows. Collar and Guzmán-Ríos also identify the discharge of scoured bottom material as threat to water quality in the downstream reach (op cit., p.15-22).

Collar and Guzmán-Ríos report siphoning bottom sediments has successfully restored reservoir capacity, primarily in the Peoples Republic of China (op cit., p. 15-23). A flexible large diameter hose is placed over or through the dam. One end moves freely within an area inside the reservoir. The other end is placed at the toe of the dam. When the siphon is primed, there is a continuous discharge of sediment laden water downstream. The process is not dependent upon storm flows for its efficacy, and therein lies a potential problem. With movement of bottom sediments at average flows or less, downstream deposition will be higher than normal for a given flow. Also, excessive oxygen demand may result downstream (Ibid.). Such conditions would not be allowed under this nation's environmental regulations. In a system involving three reservoirs and a stressed estuary, the technique is environmentally unacceptable.

No information about the cost of using the siphoning technique was located. Its simplicity suggests that the cost would be modest. However, given the negative environmental impacts, siphoning must be ruled out as a viable alternative for use in the Chesapeake Bay basin.

Capping/Fixing of Bottom Sediments

Capping of contaminated sediments in open-water disposal sites with clean dredged material is a well understood and approved disposal practice. It is considered by the Corps of Engineers as an appropriate contamination control measure for minimizing impacts on benthic organisms (Herbich, 1992, p. 9.75-9.78). A somewhat analogous process involves chemically or physically treating contaminated sediments *in situ* so as to render them harmless (inert) to the surrounding environment. Such processes are termed 'fixation' or 'stabilization'. Many of the newer sediment treatment technologies have been catalogued as part of Environment Canada's Great Lakes Cleanup Fund program (SEDTEC, 1994, p. x). The key consideration of these options relates to cost. All of the processes focus on dealing with highly contaminated sediments. Not surprisingly, they are quite expensive, with much of the cost related to the treatment of the containments. Herbich (Ibid.) states total cleanup costs at 15 sites ranged from \$11.50 to \$23.00/yd^3. Alternative technologies in the SEDTEC database had costs ranging from \$20 to nearly \$600 (U.S.) per cubic yard treated (op cit., p. 255, 299, 641, 715, 860).

No information was located regarding costs or any other aspects of processes undertaken strictly to stabilize bottom sediments, i.e., without attempting to deal with contaminants. However, the magnitude of the cost of such an undertaking can be roughly approximated. The surface area of the three reservoirs is 16,860 acres or more than 80 million square yards (Hainly and others, 1995, Table 2, p.5). Discussions with one of the USGS researchers indicate that the area of the reservoir bottoms is not substantially less than the surface. He also estimated that sediment covers approximately 90 percent of the bottom of Conowingo Pond, one-third of Lake Aldred and one-quarter of Lake Clarke (L. Reed, personal communication, March 30, 1995). Taken together, these estimates suggest that roughly 40 million square yards of sediment deposits would require stabilizing. If unit costs are as low as \$1 to \$2 per square yard, treatment costs will be in the \$40 to \$80 million range.

It is important to note that neither these techniques nor the flushing and siphoning approaches reduce the sediment load that ultimately reaches the bay. Following the logic set out in the Academy's report discussed earlier, the various approaches will alter either the timing or the variability of the loadings. The one imponderable at this point is whether there is a different impact on the bay between a sediment pulse from a major storm, and that produced by a slow sustained release of sediment to the bay. If such a difference is ever demonstrated, then siphoning or fixing might have a role to play. However, this is a different issue than the one we are addressing, namely, means of achieving and maintaining the nutrient reduction goals.

Land Management

In discussing remedial technologies for managing contaminated sediment, Herbich recommends that control measures at the source be considered in all cases (1992, p. 9.74). The Academy, in discussing sediment and nutrient discharges, took the position that corrective measures should focus entirely on land-use practices and other source controls in the watershed (1994, p. 11). The Technical Advisory Committee to the present study supports that view. (See minutes of January 13, 1995, meeting of the Technical Advisory Committee to the SRBC Sediment Management Study.)

The Bureau of Land and Water Conservation ("Bureau"), Pa. DEP, administers most of the Commonwealth's programs for controlling soil erosion and sediment and nutrient transport to streams from nonpoint sources. The several programs are the principal means available for reducing the quantities of sediment and phosphorus entering the streams of the state, and eventually finding their way to the Chesapeake Bay.

Much of the phosphorus is adsorbed on the surface of fine particles of sediment. Thus, efforts to control one generally results in controlling a substantial portion of the other. Within the Bureau there are programs focused on achieving the *nutrient* reduction goals of the Chesapeake Bay Program through implementation of nonpoint source BMPs within the agricultural sector. At the same time, programs for controlling erosion and sediment, authorized under the Clean Streams Law, focus primarily on sediment, with little or no emphasis on the efforts to curb the quantities of nutrients reaching the bay. In discussing land management options we will ignore this dichotomization.

Pennsylvania's Draft Nutrient Reduction Strategy (1994) relies on control of nitrogen and phosphorus from agricultural nonpoint sources for achieving the major part of the nutrient reduction goals (18.3 million pounds of nitrogen and 2.22 million pounds of phosphorus). Two existing programs, the nutrient management law and implementation of conservation practices, are expected to achieve 86 percent of the needed nitrogen reduction and 61 percent of the phosphorus reduction. The latter program includes the usual erosion control practices such as strip-cropping, terraces, filter strips, contouring, and conservation tillage while the former mandates nutrient management plan development and implementation. Two other existing programs--streambank fencing and barnyard runoff control--are expected to control approximately 3 percent of the nitrogen and 2 percent of the phosphorus reduction. Pennsylvania expects that the remainder of the reduction goals, (2 million pounds of nitrogen and 800,000

pounds of the phosphorus), will be met through implementing additional options, including, possibly, point source controls.

The draft cost-effectiveness analysis indicates that the Commonwealth can reach its nutrient reduction goals in the Susquehanna basin by implementing a mix of agricultural nonpoint source practices and retrofitting selected point source facilities (Seay, 1995, p. vi). Pa. DEP will not include the point source and other options in its strategy until additional refining of the point source nutrient discharge data is completed (Pa. DEP, 1994, p. 16-21).

Stemming the upward pressures on the cap after equilibrium is reached in Conowingo reservoir can be approached in several ways. Several possibilities are discussed below.

Expansion of Standard Erosion Control Practices

One approach to expanding sediment and nutrient reduction efforts is by "doing more of the same." Increasing the levels of technical and educational assistance, and increased cost-sharing budgets may induce additional program participation. While the magnitude of the response to the increased efforts will be difficult to estimate, some increase seems certain. There is no hint that the agricultural sector is saturated with these practices.

It is known that some BMPs are installed either without governmental assistance, or through government programs not tracked by Pennsylvania's database. Development of means for documenting such installations will increase the known base of such efforts.

If sediment control efforts are to be effective upstream of the hydropower reservoirs, it is probable that additional means for trapping sediments must be found. Such systems will complement the nutrient reduction programs. Three possibilities are discussed below.

Nutrient and Sediment Control System

Among the innovative newer approaches is a system developed and patented by the Soil Conservation Service (now the Natural Resources Conservation Service) of the U.S. Department of Agriculture. Named the "Nutrient and Sediment Control System" (NSCS), it consists of a sediment basin, grassed buffer, a vegetated shallow pond, a deep pond, and a vegetated "polishing" area connected in series (DuPoldt and others, 1993, p.1). The system utilizes both biological and physiochemical treatments. Its goal is to maximize the reduction of total and soluble phosphorus as well as reducing nitrogen, organic matter, bacteria, and fine sediments that reach streams during storm events. An NSCS is intended to be installed below a cropland watershed that already has conventional conservation practices installed (op cit, p. 1-2,6). Field results in Maine show that the system can remove 90 percent of total phosphorus and suspended solids during storm events (Ibid.).

While much of the descriptive material about the system assumes a location below croplands, the developers note it may also provide supplemental treatment in other settings, such as controlling urban area and barnyard runoff (op cit., p. 1).

Cost analysis of NSCS is based on an assumed useful life of 25 years. Construction costs have ranged between $14,000 and $35,000. Amortized construction costs are $17 to $22 per acre of protected area per year. Annual maintenance costs are modest, averaging $50 per system (op cit., p. 14, 16).

We recommend that the Department of Environmental Protection install and monitor NSCSs at several locations in the Susquehanna drainage in order to determine their effectiveness and costs. Perhaps Section 319H funds could be used to underwrite the demonstration projects. A technical note describing the system in detail (DuPoldt and others, 1993) is attached to the present report as Appendix C.

Sediment Detention Structures

Another means for reducing the sediment/nutrient loads that reaches the watercourse involves installing a number of sediment detention structures throughout the Susquehanna River basin. Logic suggests that such structures be concentrated in those areas of the basin producing the greatest quantities of sediment from erosion. (Identifying such areas will be aided by the results given in the reports by Ott and others [1991], and Petersen and others [1991], and the ongoing work within SRBC and Pa. DEP that continues these lines of investigation.)

Sedimentation basins can retain large proportions of the sediments entering them. The retention efficiency of such basins is a function of their size and shape as well as the flow velocity and particle size of the material passing through the structure. We also know pollutants adsorb selectively to the finer soil particles, i.e., clays and silts. Generally, sediment eroded from cropland contains a higher percentage of finer, less dense particles than its parent soil. Such selective erosion can increase the delivery of pollutants per ton of sediment delivered to the watercourse (USEPA, 1993, p. 2-7). This line of reasoning might lead one to conclude that while sediment retention basins are effective means of trapping the bulk of the larger, more dense particles, a lower percentage of nutrients traveling with the finer particles will be captured. However, there is some contrary evidence. Foster, Young and Neibling (1985) report:

> "Most agricultural soils are cohesive and have agents that bond primary particles of clay, silt, and sand into aggregates. When soil is eroded, the sediment is composed of a mixture of aggregates and primary particles" (p.133).

They also observe:

> "Experimental data show that sediment is composed of both aggregates (conglomerates of clay, silt, and sand) and primary particles, but aggregates frequently predominate" (p. 134).

Finally, calling attention to the fact that the *surface area* of clay-sized particles is 5 to 200 times greater than that of silt-sized particles, they conclude:

"...a slight change in clay content in the sediment can greatly change its potential for transporting soil-adsorbed chemicals" (Ibid.).

Meyer, Line and Harmon confirmed these findings experimentally (1991). In a study of intensively cropped soils native to Alabama, Mississippi, or Iowa, they found that:

"the size distribution of primary particles in the soils and the sediment were usually very similar. For soils with medium to high clay contents, about half of the sediment was sand sized and was dominantly in the form of aggregates."

They concluded:

"These coarse aggregates contained much of the eroded clay, so control practices that trap coarse sediment have a major potential to reduce losses of nutrients and pollutants associated with clay particles."

Thus, sediment retention structures appear to be a technologically feasible means of keeping sediment and adsorbed nutrients close to the source, and away from the mainstem of the river.

Even though structures generally are more costly than cultural practices, the Chesapeake Bay Program Nutrient Reduction Strategy Reevaluation ("Report No. 8") recognizes that edge-of-field BMPs that reduce pollutant delivery into streams have a role in systems that combine them with other measures (1993, p.101).

Any program that intends to use sediment detention basins as a part of a resource management system can at least partially overcome the cost limitations associated with structures by relying on smaller sized basins used in connection with practices such as conservation tillage and nutrient management (i.e. proper fertilizer/manure application rates, timing, and methods).

The concept of utilizing smaller detention structures suggests some interesting possibilities. At one time the USDA cost shared the installation of small farm ponds for purposes such as irrigation water supply or livestock watering. Some of these were installed *in* small tributary streams that happened to flow through a farm. Naturally, over time these ponds have acted as *sediment traps*, catching and detaining a portion of the soil from the watershed above them. Given their location, well up in the major subbasins of the Susquehanna, one would expect to find phosphorus and perhaps pesticides adsorbed on the trapped sediment. However, more exotic toxics should be rare if not nonexistent. Thus, the trapped sediment would be a useful soil amendment if it could be returned to the area from which it came. The practicality of such an approach should be explored. We propose the following trials be made under Pa. DEP's auspices.

Install six new (or rehabilitate existing) ponds of different sizes, located in different soil types, and with different watershed cover. Install complementary nonstructural BMPs in the watershed. Determine the quantity of sediment that accumulates over time, and its chemical

composition. Estimate the nutrient value of the sediment as a soil amendment. Determine the costs of installing these units and the periodic removal of the sediment back to the land. Demonstrate ways in which such sediment traps can be managed so as to be environmentally acceptable.

A major consideration for such traps is the technique used to recover the sediment deposits. Clearly, if mechanical means of excavation are employed, (e.g. front-end loader), the pond would first have to be drained and allowed to partially dry. Small self-propelled hydraulic dredges are now available that can remove the trapped sediment without reducing the water level, and pump it to a storage site on the shore. From there it can be returned to the fields by any of several commonly available means.

Dredges of the size and type envisioned here are available at costs in the range of $72,000 to $75,000 (Personal comm., S.H. Sells, Crown Pump and Dredge, April 4, 1995). They are readily transported on trailers, usually without special permits. These units are capable of moving 50 to 80 cubic yards of sediment per hour. Their services could be provided by the private sector, or as part of a sediment reduction program of the Commonwealth.

It difficult to estimate unit costs of operating the small dredges. Their supplier notes that costs are highly job-specific, depending on factors such as access to the pond, terrain, pumping distance and head, and spoil disposal options. The information in the following table develops a range of costs that is thought to encompass most operating circumstances:

H & H Pump, "LITTLE MONSTER" DREDGE ASSUMPTIONS: Investment cost: $73,500; Useful life: 15 years; Cost of capital: 10%; Dredging rate: 63.5 cubic yards per hour			
Annualized investment cost: $9,663; Fuel cost: $3.90 per hour			
Annual Hours of Operation	$ per hour (Annual capital & fuel)	$ per cubic yard	$ per acre-foot
500	$23.23	$0.36	$576
1,000	$13.56	$0.21	$340
2,000	$8.73	$0.13	$210

(Neither operator labor nor O&M costs are included.)

The proposed system has the following incentives that should help make it attractive to farmers:

- Soil and nutrients are returned to the land.
- A reduction in the amount of purchased fertilizer needed.
- The value to the farmer of an additional water source of desired size and location.
- Subsidies for the construction and maintenance of the ponds may be needed.

Management of both types of sediment detention structures discussed above includes periodic removal of the sediment and its particle-bound phosphorus. The nutrient-rich (and

presumably toxics-poor) sediment will be disposed of by spreading it on cropland. Obviously, this must be done when the fields are open. Before spring planting or after fall harvesting are possible times.

There is at least anecdotal evidence which suggests that particle-bound phosphorus in bottom sediments is released to the water column during the warm summer months (G.B. Wolff, personal communication, May 30, 1995). If this is the case, the sediment traps should be cleaned out before spring planting in order to maximize the nutrient value of the material returned to the land. Therefore, we recommend careful monitoring at the demonstration sites of the phosphorus levels in the bottom sediments and the overlaying water column, to establish if there are seasonal differences.

Erosion and Sediment Pollution Control Program

The erosion and sediment pollution control program (E&S) of the Bureau encompasses many different types of earthmoving activities, including industrial, commercial and residential development, highway construction, agriculture, and lumbering. To date the *nutrient* reduction impacts of these efforts have not been included in the tally of progress toward reaching the CPB's goal. This is so, at least in part, because the impacts of the sediment and erosion control efforts are not quantified in a way that fits into the Bay Program's accounting system. As a result the Commonwealth does not receive credit for the nutrient reduction impacts of the efforts.

We urge that the department give greater prominence to its E&S untertakings. This can be done with the following sorts of actions:

- Increase the interactions between the E&S and the nonpoint source management programs.
- Give explicit recognition that the E&S efforts, particularly in the areas of urban/suburban construction and development, are part of the *nutrient* reduction program.
- Develop ways to gather the data needed to make estimates of the quantities of nutrients kept from the Bay as a result of the E&S program.

Costs of BMPs

This study attempts to identify sediment and nutrient reduction technologies that are acceptable from technological, environmental, and financial perspectives. As discussed earlier, the concept of dredging the hydropower reservoirs appears deficient in each regard. The notion of fixing bottom sediments fails principally for cost reasons. Other in-situ possibilities discussed were deemed unacceptable for their environmental impacts.

Estimating the costs of the conventional BMPs applied to agricultural nonpoint sources, as well as point sources, is not a simple undertaking. The nutrient loads that reach the edge of a watercourse vary widely by type of nutrient, land use, and location in the basin, i.e., CBP Watershed Model segment. To this complexity, add the fact that edge-of-field nutrient reduction effectiveness of the various BMPs (or combinations of BMPs) vary widely. It is precisely these

complexities that necessitate the use of elaborate models to approximate the transport and deposition of suspended sediments and nutrients to the Chesapeake from its tributaries.

The best available nutrient reduction cost estimates are in the report on cost-effectiveness analyses prepared by SRBC for Pa. DEP (Seay, 1995). The report discusses the sources and limitations of the BMP unit costs (op cit., p. 5-6). Table 3 of the cost-effectiveness analysis, (Ibid.), (included in the present report as Appendix D), contains the results of a linear programming problem. For that reason, it contains BMPs with widely differing unit costs ($ per ton of nutrient removed). To explain why this is so is beyond the scope of this paper. However, for those readers interested in gaining a better understanding of the process, a good nontechnical description can be found in chapter 11 of Stokey and Zeckhauser (1978).

When using the cost-effectiveness results, it is important to keep in mind that each BMP (with the sole exception of chemical treatment to remove phosphorus from point sources) causes a reduction in both phosphorus *and* nitrogen loads. In fact, the BMPs of concern provides significantly higher nitrogen reduction than phosphorus reduction. Nitrogen to phosphorus ratios range from 7:1 to 131:1, and averaged 15:1 overall for the nonpoint source BMPs. Therefore the estimated annual cost for each BMP was divided by the total nutrient reduction in pounds to calculate a unit cost *per pound of nutrient reduction.* By assuming that the unit cost is relevant to either nutrient, we may make cost estimates where the primary concern is with one nutrient. Since the focus of the present work is sediment, particle-bound phosphorus is the nutrient of interest.

Utilizing the information in the table in Appendix D and the calculated unit costs, the following cost ranges for phosphorus reduction were calculated for the various BMPs and BMP combinations. "Average" indicates cost differences across land uses.

BMP/BMP Combination	**$ per Ton Phosphorus**
FOR NONPOINT SOURCES	
Conversion of highly erodible land to permanent pasture	$16,200 (average)
Nutrient management	$5,560 (average)
Farm Plan	$6,180
Nutrient management + farm plan	$6,280 (average)
Conservation tillage + farm plan + nutrient management	$8,040
Animal waste management	$39,600
Forest BMPs	$15,180
ALL NONPOINT SOURCE BMPs	$10,720
FOR POINT SOURCES	
Chemical phosphorus removal	$8,575
ALL POINT SOURCE BMPs	$28,600
TREATING PHOSPHORUS FROM ALL SOURCES	**$13,400**

As noted earlier, we do not have a long-term (decades) record of the sediment load transported down the Susquehanna to the Bay. Of special interest is the quantity of sediment and

nutrients still being trapped in Conowingo Reservoir. The phosphorus in this annual inflow will put upward pressure on the cap after equilibrium is reached. Ott and others estimate the trapped quantities to be 4,400 million pounds of sediment, 3.57 million pounds of phosphorus, and 3 million pounds of nitrogen annually (1991, Table 64, p. 155). However, the Academy study suggests that these quantities are overestimated for periods of "normal" flows (1994, p.7). According to Gross and others (1978, p. 107-8), at least half, and usually two-thirds, of the suspended sediment transported past Harrisburg when peak daily discharges are below 400,000 cfs does not pass Conowingo dam. McLean and others (1991, p. 155) concluded that in the absence of episodic storm events, 33 to 63 percent of the sediment introduced into Conowingo pond remain there. The Academy authors (1994, p.9) point out that the work of McLean and his colleagues focused on the clay/silt fraction of the sediments in the reservoir, leading to a lower estimate of the trapping efficiency. However, this is precisely the fraction with which most of the particle-bound phosphorus is transported.

The range of trapping efficiencies suggested by the several studies lead to the conclusion that, under normal flows, sediment deposition in the reservoir lies between 2,000 and 4,000 million pounds per year. From information in the report by Ott and others, we estimate that particulate phosphorus is 67 percent of the total phosphorus load passing Harrisburg (1991, Table 43, p. 100). Applying this percentage to the total phosphorus load passing Harrisburg (op cit., Table 64), and using the range of trapping efficiencies, the quantity of phosphorus deposited in Conowingo Pond can lie between 1.9 and 3.7 million pounds (962 and 1,836 tons) per year.

Using the phosphorus treatment costs derived above, the total cost of treating the additional particulate phosphorus that will reach the bay after equilibrium is reached can range over the following amounts:

PRACTICE(S)	962 TONS P (millions of dollars)	1,836 TONS P (millions of dollars)
Nutrient Management	$ 5.35	$ 10.2
Farm Plan	5.95	11.3
Nutrient Management + Farm Plan	6.04	11.5
Conservation Tillage + Farm Plan + Nutrient Management	7.73	14.8
Animal Waste Management	38.8	72.7
Forest BMPs	14.6	27.9
All Nonpoint Source Practices	10.3	19.7
Chemical Phosphorus-only treatment	8.2	15.7
All Point Source BMPs	27.5	52.5
From All Sources-(PS and NPS)	12.9	24.6

Clearly, the costs vary widely, depending upon the mix of BMPs employed. The chemically based removal of phosphorus from point sources and the nutrient management-farm plan-conservation tillage combinations should be exploited as fully as possible. We are hopeful that the suggested sediment detention structures will also prove competitive.

SUMMARY AND RECOMMENDATIONS FOR SEDIMENT AND NUTRIENT LOAD REDUCTIONS

Expansion of Existing Efforts

Once programs are in place to achieve the 40 percent nutrient reduction goals, the task of maintaining the cap remains. As mentioned earlier, one aspect of such efforts is to continue to expand participation in existing programs for installing structural and nonstructural BMPs. A combination of more education and technical assistance, financial assistance, and more rigorous enforcement should induce greater participation.

Pa. DEP is reevaluating its point source program (Pa. DEP, 1994, p. 16). Retrofitting selected facilities with phosphorus-only removal technology contributes to achieving the 40 percent reduction in a cost-effective manner (Seay, 1995, p. 20). Applying this technology at additional facilities should reduce phosphorus loads reaching the bay by amounts that are readily quantifiable. Any such reduction will assist with maintaining the cap.

Target Installations To "Hot Spots"

Pollution control efforts should focus on areas that are major sources of agricultural nonpoint problems. Davenport and his associates (1991) call attention to the progress being made in improving technologies for targeting erosion control efforts for water quality purposes. Advances in methods that replace the universal soil loss equation and model areas of high erosion will greatly enhance our capacity to specify the impact of erosion on receiving waters. With such improved technical capabilities, the result will be both better water quality and more cost-effective programs.

Targeting has been a part of Pennsylvania's efforts since the inception of the Chesapeake Bay program. Petersen and his colleagues (1991) ranked 104 watersheds in the Commonwealth according to their potential as sources of agricultural pollution via surface waters. We understand that Pa. DEP staff is continuing to refine this process. Any improvement that can be made in the targeting strategy will add to the Commonwealth's capacity to reduce sediment and nutrients reaching the streams in a cost-effective way.

Field Tests of Sediment/Nutrient Detention Structures

Two structural BMPs have been identified above as having particular promise for reducing the sediment and nutrient loads that reach the watercourse. The first utilizes small, mobile dredges to remove accumulated materials from existing or specially constructed sediment detention ponds. While very appealing conceptually, no data exists about their effectiveness or cost. Suppliers of the dredges advise that unit costs of operating the units are highly site and job specific. For these reasons we recommend that demonstration test sites be established and

monitored in a variety of soil and land use settings. It should be possible to verify their effectiveness and narrow the range of costs in a reasonable period of time.

The second system, USDA's "Nutrient and Sediment Control System," (NSCS), has not been field tested in this region. USDA personnel involved in the development of the system tell us they see no technical reasons that might limit its use in the Susquehanna basin. However, detailed cost and sediment/nutrient trapping data are not available. Therefore, we recommend that Pa. DEP, working with Natural Resources Conservation Service and Penn State University researchers, develop one or more demonstration test sites where the capabilities and costs of the system can be documented.

If the demonstration efforts are to produce conclusive findings, it is essential that a carefully planned monitoring program be put in place and diligently executed.

Continue Efforts to Expand Erosion and Sediment Control Programs

The Bureau of Land and Water Conservation, Pa. DEP, should continue its expanded program of enforcing the state's Erosion and Sediment Pollution Control Program. Simultaneously, the Bureau should continue efforts to develop better estimates of the quantities of nutrients and sediment controlled by the program.

Control of polluted runoff from urban sources can be an important component of the total program. Where practicable, local units of government should be encouraged to include control practices in their building and subdivision ordinances. Chapter 4 of the U.S. EPA guidance document (1993) contains an extensive discussion of sediment and nutrient management measures for urban areas.

Support Efforts to Improve Modeling of Reservoirs

The target nutrient reduction loads Pennsylvania seeks to achieve under the Chesapeake Bay agreement are derived from the CBP watershed model. The Bay Program, under the lead of its modeling subcommittee, continues to update and refine the accuracy and precision of the results generated by the model. In Phase III of the modeling effort researchers from the Corps of Engineers' Waterways Experiment Station (WES) are attempting to refine the representation of nutrients as they pass through the lower Susquehanna reservoirs and into the upper bay. The Phase IV workplan, while still focusing on nutrient transport, calls for refining the model's limited capability to describe sediment transport. We submit that a better representation of suspended sediment loads passing through the reservoirs is needed. Apparently, the Phase V workplan, if funded, will produce a more fully integrated sediment transport and water quality model. The SRBC is aware of federal funds that *may* become available in the next fiscal year that could support that phase of the work. We recommend that Pa. DEP support such an undertaking, should the funds become available. An improved capability to predict nutrient and sediment loads in the era after the year 2000 will aid the Commonwealth in planning its efforts to maintain the nutrient cap.

Prepare to Study the Impacts of the Next Major Flood Event

It is probable that the studies of the impacts of Tropical Storm Agnes on the Chesapeake Bay watershed were the first in the history of the hemisphere to attempt to document the effects of a major storm on a large region. Much of this information is found in the papers collected as an appendix volume, The Effects of Tropical Storm Agnes on the Chesapeake Bay Estuarine System, prepared by the Chesapeake Research Consortium, Inc. under contract to the Baltimore District, Corps of Engineers (1975). The preface to the appendix notes the hurried way in which the data collection had to be undertaken:

> It is worthy of note that [the Chesapeake Bay Institute, Chesapeake Biological Laboratory, and the Virginia Institute of Marine Science], the three major laboratories oriented toward research on Chesapeake Bay, undertook extensive data gathering programs requiring sizable commitments of personnel and equipment without assurance that financial support would be provided. The emergency existed and the scientists recognized both an obligation to assist in ameliorating the destructive effects and a rare scientific opportunity to better understand the ecosystem. They proceeded to organize a coordinated program in hope that financial arrangements could be worked out later. Fortunately, their hopes proved well founded.
>
> (op cit., p. v)

We recommend that Pa. DEP take the lead in developing *before the fact* a plan of study that can be quickly set into motion when the next major flood event occurs in the Chesapeake basin. The development of such a plan could be coordinated by a regional entity such as the Scientific and Technical Advisory Committee (STAC) to the Chesapeake Bay Program, with staff support from the Chesapeake Research Consortium. Such a plan would anticipate the next storm event, and permit the gathering of a variety of data during and subsequent to the storm. This knowledge should improve our understanding of the interactions between the Susquehanna and the Bay during extreme events.

REFERENCES CITED

Academy of Natural Sciences of Philadelphia, 1994, Issues Regarding Estimated Impacts of the Lower Susquehanna River Reservoir System on Sediment and Nutrient Discharge to Chesapeake Bay: Report No. 94-20, 20 p.

Baltimore District, Corps of Engineers, Department of the Army, 1975, Impact of Tropical Storm Agnes on Chesapeake Bay: 2 volumes: Summary and Technical Appendix.

Biggs, R.B. and Howell, B.A., 1984, The Estuary as a Sediment Trap, p. 107-129, *in* Kennedy, V.S., ed., The Estuary as a Filter: Orlando, Academic Press.

Blankenship, K., 1994, 1994 freshet brings wave of ills to the Bay: *Bay Journal*, v. 4, no. 6, p.1, 10-11.

Chesapeake Bay Program Nutrient Reduction Strategy Reevaluation (CBPNRS) Report #8, 1993, Financial Cost Effectiveness of Point and Nonpoint Source Nutrient Reduction Technologies in the Chesapeake Bay Basin: (CBP/TRS 84/93), Annapolis, 109 p. and 9 appendices.

Collar, P.D. and Guzmán-Ríos, S., 1991, Sedimentation Rates and Capacity Restoration Options, Lago Loiza, Puerto Rico, *in* Fan, S-s and Kuo, Y-h, eds., Proceedings of the Fifth Federal Interagency Sedimentation Conference (2 vols.): Subcommittee on Sedimentation, Interagency Advisory Committee on Water Data, Las Vegas, March, p. 15-17 to 15-25.

Davenport, T.E., Kirschner, R., Meek, J.A., and Kirschner, L.T., 1991, Soil Loss Limits and Water Quality, *in* Fan, S-s and Kuo, Y-h, eds., Proceedings of the Fifth Federal Interagency Sedimentation Conference (2 vols.): Subcommittee on Sedimentation, Interagency Advisory Committee on Water Data, Las Vegas, March, p. 13-52 to 13-57.

Donigian, A.S., Jr., Bickwell, B.R., Patwardhan, A.S., Linker, L.C., Alegre, D.Y., Chang, C-h, and Reynolds, R., 1994, Watershed Model Application to Calculate Bay Nutrient Loadings--Final Findings and Recommendations: U.S. EPA, Region III, Chesapeake Bay Program Office, Annapolis, 283 p.

DuPoldt, C.A., Jr., Terrell, C.R., Franzen, R.W., and Wengrzynek, R.J., Jr., 1993, Nutrient and Sediment Control System: Environmental Quality Technical Note No. N4, NRCS-USDA-Chester, Pa., 19 p.

Federal Emergency Management Agency, 1979, Flood Insurance Study--Town of Lower Chanceford, York County, Pennsylvania: Federal Insurance Administration, 17 p.

Foster, G.R., Young, R.A., and Neibling, W.H., 1985, Sediment Composition for Nonpoint Source Pollution Analyses: *Transactions of the ASAE*, v. 28, no. 1, p. 133-146.

Goldman, C.R. and Horne, A.J., 1983, Limnology: New York, McGraw Hill Book Co., 464 p.

Gross, M.G., Karweit, M., Cronin, W.B., and Schubel, J.R., 1978, Suspended Sediment Discharge of the Susquehanna to Northern Chesapeake Bay, 1966 to 1976: *Estuaries*, v. 1, no. 2, p. 106-110.

Hainly, R.A., Reed, L.A., Flippo, H.N., Jr. and Barton, G.J., 1995, Deposition and Simulation of Sediment Transport in the Lower Susquehanna River Reservoir System: U.S. Geological Survey Water-Resources Investigations Report 95-4122, 39 p.

Herbich, J.B., ed., 1992, Handbook of Dredging Engineering: New York, McGraw-Hill, Inc..

Hobbs, C.H., Halka, J.P., Kerhin, R.T., and Carron, M.J., 1992, Chesapeake Bay sediment budget: *Journal of Coastal Research*, v. 8, no. 2, p. 292-300.

Lang, D.J., 1982, Water Quality of the Three Major Tributaries to the Chesapeake Bay, The Susquehanna, Potomac, and James Rivers, January 1979 - April 1981: U.S. Geological Survey Water-Resources Investigation 82-32, 64 p.

Linsley, R.K., Franzini, J.B., Freyberg, D.L., and Tchobanoglous, G., 1992, Water-Resources Engineering, (4th. ed.): New York, McGraw-Hill, Inc., 841 p.

Matuszeski, W., 1995, Letter to K.R. Gentzler, Pa. DEP, dated May 30, 1995, concerning detailed nutrient loading information for all Pennsylvania basins. 4 p.

McLean, R.I., Summers, J.K., Olsen, C.R., Domotor, S.L., Larsen, I.L., and Wilson, H., 1991, Sediment Accumulation Rates in Conowingo Reservoir as Determined by Man-Made and Natural Radionuclides: *Estuaries*, v. 14, no. 2, p. 148-156.

Meyer, L.D., Line, D.E., and Harmon, W.C., Particle Sizes of Sediment From Cropland Soils, *in* Fan, S-s and Kuo, Y-h, eds., Proceedings of the Fifth Federal Interagency Sedimentation Conference (2 vols.): Subcommittee on Sedimentation, Interagency Advisory Committee on Water Data, Las Vegas, March, p. PS-64 to PS-71.

Ott, A.N., Takita, C.S., Edwards, R.E., and Bollinger, S.W., 1991, Loads and Yields of Nutrients and Suspended Sediment Transported in the Susquehanna River Basin, 1985-89: Susquehanna River Basin Commission, Publication No. 136, 254 p.

Pennsylvania Department of Environmental Protection, 1994, Pennsylvania's Draft Nutrient Reduction Strategy for the Susquehanna and Potomac River Basins: DEP # 1656, 55 p.

Peterson, G.W., Hamlett, J.M., Baumer, G.M., Miller, D.A., Day, R.L., and Russo, J.M., 1991, Evaluation of Agricultural Pollution potential in Pennsylvania Using a Geographic Information System: Final Report ME89279 prepared for Pa. DEP, University Park, Pa., Environmental Resources Research Institute, ER9105, 60 p.

Schubel, J.R. and Pritchard, D.W., 1986, Responses of the Upper Chesapeake Bay to Variations in Discharge of the Susquehanna River: *Estuaries*, v. 9, no. 4A, p. 236-249.

Schuleen, E.T. and Higgins, C.R., 1953, Analysis of Suspended-sediment Measurements for Lake Clarke, Inflow and Outflow, 1948-1953: Pennsylvania Power and Light Co. Report 970.

Seay, E.E., 1995, Nutrient Reduction Cost-Effectiveness Analyses, Component 2, Nutrient Reduction Strategy: Final Report on Pa. DEP contract no. ME92547, SRBC Publication No. 161, 261 p.

SEDTEC--Sediment Treatment Technologies Database (3rd ed.), 1994: Site Remediation Division, Wastewater Technology Centre, Burlington, Ontario, Canada, 884 p.

Stokey, E. and Zeckhauser, R., 1978, A Primer for Policy Analysis: New York, W.W. Norton, 356 p.

Takita, C.S. and Edwards, R.E., 1993, Nutrient and Suspended-sediment Loads Transported in the Susquehanna River Basin, 1990-1991: Susquehanna River Basin Commission, Publication No. 150, 57 p.

U.S. Environmental Protection Agency, 1993, Guidance Specifying Management Measures For Sources of Nonpoint Pollution in Coastal Waters: Washington, DC, Office of Water, EPA 840-B-92_002.

Williams, K.F., and Reed, L.A., 1972, Appraisal of Sedimentation in the Susquehanna River Basin: U.S. Geological Survey Water-Supply Paper 1532-F.

Zynjuk, L.D., 1994, Record Flow Transports High Load of Nutrients and Sediment into Chesapeake Bay: S.R.B.C., *Susquehanna Guardian*, v. 3, no. 2, p. 1-2

APPENDIX A

DEPOSITION AND SIMULATION OF SEDIMENT TRANSPORT IN THE LOWER SUSQUEHANNA RIVER RESERVOIR SYSTEM

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 95-4122

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DEPOSITION AND SIMULATION OF SEDIMENT TRANSPORT IN THE LOWER SUSQUEHANNA RIVER RESERVOIR SYSTEM

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Lemoyne, Pennsylvania
1995

U.S. DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS AND ABBREVIATIONS

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square foot (ft^2)	0.09294	square meter
square mile (mi^2)	2.590	square kilometer
acre	0.4047	hectare
	Velocity	
foot per second (ft/s)	0.3048	meter per second
mile per year (mi/year)	1.609	kilometer per year
	Volume	
cubic foot (ft^3)	0.02832	cubic meter
acre-foot (acre-ft)	1,233	cubic meter
	Flow	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
	Mass	
ton, short	0.9072	megagram
	Temperature	
degree Fahrenheit (°F)	°C = 5/9 × (°F-32)	degree Celsius
	Pressure	
pounds per square foot (lb/ft^2)	0.04788	dynes per square meter
	Density	
pounds per cubic foot (lb/ft^3)	16.02	kilograms per cubic meter

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NVGD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

DEPOSITION AND SIMULATION OF SEDIMENT TRANSPORT IN THE LOWER SUSQUEHANNA RIVER RESERVOIR SYSTEM

by Robert A. Hainly, Lloyd A. Reed, Herbert N. Flippo, Jr., and Gary J. Barton

ABSTRACT

The Susquehanna River drains 27,510 square miles in New York, Pennsylvania, and Maryland and is the largest tributary to the Chesapeake Bay. Three large hydroelectric dams are located on the river, Safe Harbor (Lake Clarke) and Holtwood (Lake Aldred) in southern Pennsylvania, and Conowingo (Conowingo Reservoir) in northern Maryland. About 259 million tons of sediment have been deposited in the three reservoirs. Lake Clarke contains about 90.7 million tons of sediment, Lake Aldred contains about 13.6 million tons, and Conowingo Reservoir contains about 155 million tons. An estimated 64.8 million tons of sand, 19.7 million tons of coal, 112 million tons of silt, and 63.3 million tons of clay are deposited in the three reservoirs. Deposition in the reservoirs is variable and ranges from 0 to 30 feet.

Chemical analyses of sediment core samples indicate that the three reservoirs combined contain about 814,000 tons of organic nitrogen, 98,900 tons of ammonia as nitrogen, 226,000 tons of phosphorus, 5,610,000 tons of iron, 2,250,000 tons of aluminum, and about 409,000 tons of manganese.

Historical data indicate that Lake Clarke and Lake Aldred have reached equilibrium, and that they no longer store sediment. A comparison of cross-sectional data from Lake Clarke and Lake Aldred with data from Conowingo Reservoir indicates that Conowingo Reservoir will reach equilibrium within the next 20 to 30 years. As the Conowingo Reservoir fills with sediment and approaches equilibrium, the amount of sediment transported to the Chesapeake Bay will increase. The most notable increases will take place when very high flows scour the deposited sediment.

Sediment transport through the reservoir system was simulated with the U.S. Army Corps of Engineers' HEC-6 computer model. The model was calibrated with monthly sediment loads for calendar year 1987. Calibration runs with options set for maximum trap efficiency and a "natural" particle-size distribution resulted in an overall computed trap efficiency of 34 percent for 1987, much less than the measured efficiency of 71 percent.

INTRODUCTION

The District of Columbia and the States of Pennsylvania, Maryland, and Virginia have agreed to a 40-percent reduction in controllable nutrient loads to the Chesapeake Bay by the year 2000. The load of nutrients transported to the bay depends, in large part, on the load transported by the Susquehanna River, the largest freshwater contributor to the bay. The reservoir system on the Lower Susquehanna River affects the loads of sediment and nutrients delivered to Chesapeake Bay, but the magnitude and length of the effects are not known.

As part of the Chesapeake Bay Program, the Bureau of Land and Water Conservation of the Pennsylvania Department of Environmental Resources and the U.S. Geological Survey (USGS) cooperated in a study to evaluate deposition of sediment, nutrients, and selected metals in the three reservoirs on the Lower Susquehanna River. The study was conducted during the summer and fall of 1990.

Purpose and Scope

The quantity and chemistry of sediment in the reservoirs formed by the Safe Harbor, Holtwood, and Conowingo hydroelectric dams is evaluated in the report. The report presents a comparison of historical reservoir-bed elevations with elevations obtained during this study, and an estimate of the remaining sediment storage capacity. The results of calibrating a model to calculate deposition and scour in the reservoirs during storms also are presented.

Data from the seismic-reflection profiling, data obtained during the collection of core samples, and historical data (Whaley, 1960) were used to map the thickness of bed sediments. The dry density and composition data determined from the core sample analyses, and the sediment thickness data were used to compute the dry weight and composition of the deposited material in each reservoir.

Description of the Study Area

The Susquehanna River drains 27,510 mi^2 in south-central New York, central Pennsylvania, and a small part of Maryland before entering the Chesapeake Bay (fig. 1). The reservoirs in the lower part of the Susquehanna drainage were formed by the construction of three hydroelectric dams on the 32-mi reach of the river between Conowingo, Md., and Columbia, Pa. (fig. 2). Conowingo Dam is in northern Maryland and forms Conowingo Reservoir, which extends into southern Pennsylvania. Holtwood Dam is upstream from Conowingo Reservoir and forms Lake Aldred. Safe Harbor Dam is upstream from Lake Aldred and forms Lake Clarke.

The climate in the Susquehanna River Basin varies considerably from central New York State to northern Maryland. The mean annual temperature ranges from 45°F in central New York to 53°F in Maryland. The mean growing season ranges from 120 days in the north to 160 days in the south (U.S. Department of Commerce, 1990). Mean annual precipitation in the basin is about 40 in. and is fairly evenly distributed throughout the year. The mean annual precipitation is highest in the lower basin and lowest in the headwaters.

Woodland covers 63 percent of the Susquehanna River Basin and is concentrated in the northern and western parts of the basin. Nineteen percent of the basin is tilled cropland, and most of the tilled cropland is in the lower basin. Extensive, cultivated areas are also along the river valleys in southern New York and northern Pennsylvania. Urban land occupies slightly more than 9 percent of the basin. Most of the urban areas are along river valleys in southern New York and central Pennsylvania.

Anthracite coal was mined in several areas of eastern Pennsylvania. Fine coal from processing plants in the mining region was a large component of the sediment transported by the Susquehanna River from the late 19th century through the early 20th century, and "river coal" was routinely dredged from pools in the river until 1972. After the hydroelectric dams were constructed on the Lower Susquehanna River, large amounts of fine coal were trapped in the reservoirs.

DESCRIPTION OF THE HYDROELECTRIC DAMS AND RESERVOIRS

Safe Harbor Dam and Lake Clarke

Safe Harbor Dam, constructed in 1931, is 32 mi upstream from Chesapeake Bay (fig. 2). Lake Clarke extends upstream about 9.5 mi from Safe Harbor, Pa., to Columbia, Pa., and has a design capacity of 150,000 acre-ft (table 1). Streamflow in excess of plant capacity is regulated by flood gates along the top of the dam west of the hydroelectric plant.

Table 1. *Physical characteristics of the three hydroelectric dams and reservoirs on the Lower Susquehanna River*

Dam	Lake or reservoir	Year completed	Elevation (feet above sea level)		Design capacity (acre-feet)	Surface area (square miles)	Maximum turbine discharge (cubic feet per second)
			Normal pool	Flood pool			
Safe Harbor	Clarke	1931	227	227	150,000	9.5	110,000
Holtwood	Aldred	1910	[1] 170	180	60,000	4.0	27,000
Conowingo	Conowingo	1928	109	109	300,000	12.8	81,000

[1] Includes 4.75-foot flash boards.

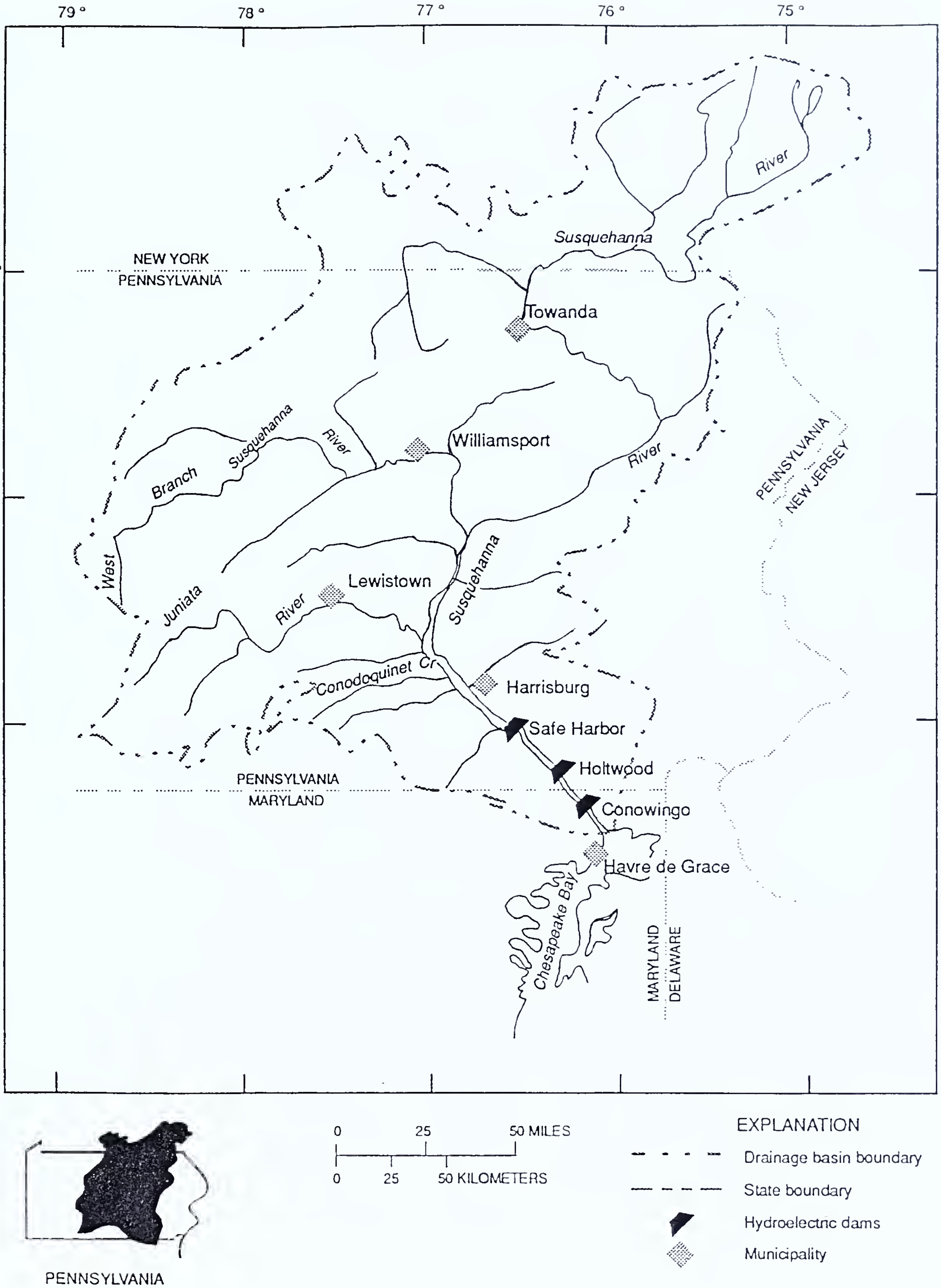


Figure 1. The Susquehanna River Basin.

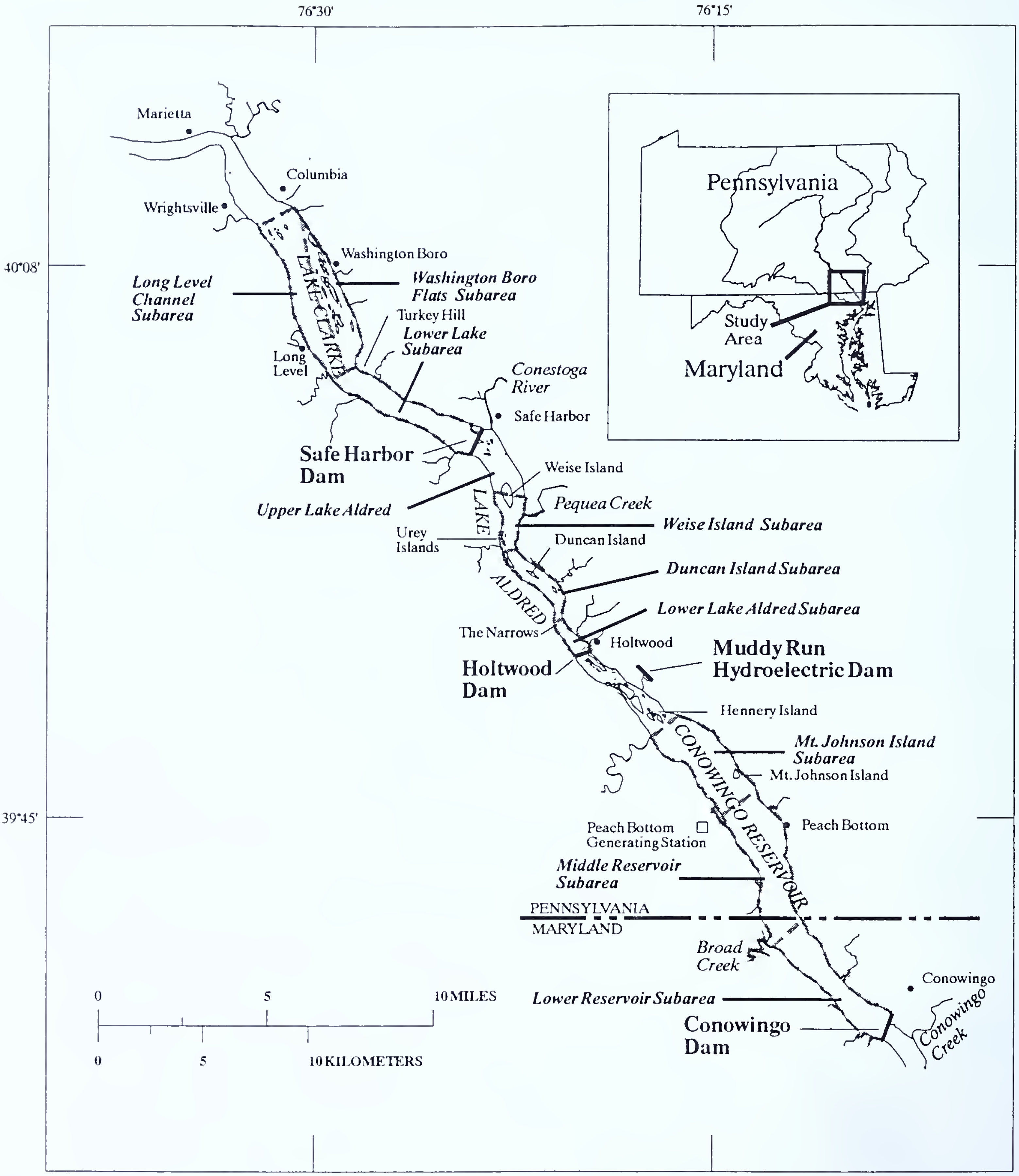


Figure 2. The location of the three hydroelectric dams on the Lower Susquehanna River.

For the purposes of this study, Lake Clarke was divided into three subareas—the Washington Boro flats, the Long Level channel, and the lower lake (fig. 2, table 2). The Washington Boro flats are along the eastern half of the lake from Washington Boro to Turkey Hill. The surface area, excluding the three large islands, is 2.7 mi^2. Lake Clarke contains many small islands with land surfaces just above the normal water level and numerous sand and coal bars with surfaces just below the normal water level. Many sand and coal bars are exposed during low water and much of the area is too shallow for boating. The Long Level channel extends along the west side of the lake from about 3 mi upstream of the community of Long Level downstream to Turkey Hill. The surface area of the Long Level channel is 3.8 mi^2. The lower lake extends from Turkey Hill to the Safe Harbor Dam and has a surface area of 3.0 mi^2.

Table 2. *Physical characteristics of the Lower Susquehanna River reservoir subareas*

Reservoir subarea	Surface area		Channel length (feet)	Maximum width (feet)	Minimum width (feet)
	(square miles)	(acres)			
	Lake Clarke				
Washington Boro Flats	2.7	1,720	24,600	4,680	800
Long Level channel	3.8	2,440	26,600	6,600	3,720
Lower Lake	3.0	1,930	22,400	5,000	3,000
Total	9.5	6,090	[1]49,000	8,840	3,000
	Lake Aldred				
Upper Lake Aldred	1.2	780	9,200	5,080	4,040
Weise Island	1.0	660	13,000	3,800	2,000
Duncan Island	1.3	830	14,000	2,700	1,200
Lower Lake Aldred	.5	290	6,400	2,800	1,200
Total	4.0	2,560	42,600	5,080	1,200
	Conowingo Reservoir				
Below Holtwood Dam	1.5	990	17,200	5,160	1,840
Mt. Johnson Island	3.6	2,310	16,600	6,840	5,120
Middle Reservoir area	4.7	3,020	23,320	7,000	5,500
Lower Reservoir area	3.0	1,890	20,440	5,500	3,100
Total	12.8	8,210	77,560	7,000	1,840

[1] The total channel length is the sum of the Long Level channel and Lower Lake subareas because the Washington Boro flats and the Long Level channel are side-by-side, and not consecutive subareas.

Holtwood Dam and Lake Aldred

The Holtwood Dam, constructed in 1910, is about 25 mi upstream of Chesapeake Bay (fig. 2). The reservoir formed by the dam, Lake Aldred, extends upstream for about 8 mi. Lake Aldred covers an area of about 4.0 mi^2 and has a design capacity of 60,000 acre-ft (table 1). Holtwood Dam was constructed without flood gates, and river flow in excess of plant capacity spills over the top of the dam to the west of the powerhouse. A coal-fired power plant was constructed adjacent to the hydroelectric plant in 1925. The coal plant had a capacity of 73,000 kilowatts and was designed to burn about 200,000 tons of river coal per year. Until 1972, most of this coal was dredged from the reservoirs.

For this report, Lake Aldred was divided into four subareas (fig. 2, table 2). The most upstream subarea, Upper Lake Aldred, extends from the Safe Harbor Dam to Weise Island and covers 1.2 mi^2. The Weise Island subarea extends from Weise Island to just below the Urey Islands. This subarea of the lake is 13,000 ft long, and the width ranges from 3,800 ft just below Weise Island to 2,000 ft at the Urey Islands. The surface area, not including Weise Island, is 1.0 mi^2. The Duncan Island subarea extends from just below the Urey Islands to the narrows. It is 14,000 ft long, and the width ranges from 2,700 ft above Duncan Island to 1,200 ft at the Narrows. The surface area is 1.3 mi^2. Lower Lake Aldred extends from the Narrows to the dam. The width of this subarea ranges from 1,200 ft at the Narrows to 2,800 ft above the dam. The surface area is 0.5 mi^2.

Conowingo Dam and Conowingo Reservoir

Conowingo Dam, constructed in 1928 about 10 mi upstream of Chesapeake Bay, is the largest hydroelectric dam and creates the largest reservoir on the river. Conowingo Reservoir has a surface area of 12.8 mi^2 and a design capacity of 300,000 acre-ft (table 1). The elevation of the river bed at the dam is about 11 ft above sea level, and the normal pool elevation is 109 ft. River flow in excess of the plant capacity is discharged through flood gates installed on the east side of the dam.

Conowingo Reservoir extends about 12 mi from the dam upstream to Hennery Island (fig. 2). A 3.2-mi section of the river separates the Holtwood Dam from the headwaters of the Conowingo Reservoir at Hennery Island. Water velocities in this river section are high, and sediment does not accumulate. The remainder of the reservoir was divided into three subareas—the Mt. Johnson Island subarea, the Middle Reservoir subarea, and the Lower Reservoir subarea (table 2).

The Mt. Johnson Island subarea extends from Hennery Island to just below the Peach Bottom Generating Station and has an average width of about 6,000 ft. The surface area is 3.6 mi^2. The Middle Reservoir subarea extends from below the Peach Bottom Generating Station to Broad Creek. The width of the Middle Reservoir subarea ranges from 7,000 ft just below the Peach Bottom Generating Station to 5,500 ft at Broad Creek, and the surface area is 4.7 mi^2. The Lower Reservoir subarea extends from Broad Creek to Conowingo Dam. The width of this subarea ranges from 5,500 ft at Broad Creek to 3,100 ft at Conowingo Creek and increases to about 4,900 ft at the dam. The surface area of the Lower Reservoir subarea is 3.0 mi^2.

PREVIOUS STUDIES

Anthracite coal was a major component of the sediment transported by the Susquehanna River from the late 19th century through the early 20th century. Mined coal was brought to the land surface, broken, and washed. At many of the coal-processing areas, the waste water from the washing operations was discharged directly to streams. An estimated 10-15 percent of the coal that was mined and run through the breakers was discharged in the wash water. Sisler and others (1928) reported that 260,000 tons of coal were dredged from the Susquehanna River in 1913 and that half of that amount had a diameter larger than 2 mm (millimeters). They also reported that continuing deposition and scour were moving a large coal bar down the river at a rate of about 3 mi per year. By 1925, dredge operators were recovering 400,000 tons of coal a year from the Susquehanna River.

Schuleen and Higgins (1953) reported the results of siltation surveys in Lake Clarke. They reported that Lake Clarke contained 144,600 acre-ft of water in 1931, and the capacity was reduced to 78,800 acre-ft in 1950. The implication is that nearly 66,000 acre-ft of water storage (about 45 percent of the design capacity) was lost because of sediment deposition during 1931-50. In 20 years, the lake trapped about 74 million tons of sediment, which is an average deposition rate of 3.7 million tons per year. Surveys completed in 1950, 1951, 1959, and 1964 indicated that the amount of sediment in Lake Clarke remained fairly constant at 74 million tons from 1950 to 1964 and that the reservoir had reached an equilibrium (E.T. Schuleen, Pennsylvania Power and Light Company, oral commun., 1965).

Schuleen and Higgins (1953) also collected suspended-sediment data from the Susquehanna River at Columbia and at Safe Harbor during 1948-53. During the 6-year period, sediment discharge at Columbia, upstream of Lake Clarke, averaged 4.46 million tons per year and the sediment discharge measured at Safe Harbor, the outflow of the reservoir, was 3.13 million tons per year.

Levin and Smith (1954) reported on a river-coal dredging operation in Lake Clarke that started in 1953. The operation was designed to dredge 1 million tons of material a year from Lake Clarke and transport it on barges to the shore where the sand and coal were separated. The dredged material was about half sand and half coal. Dredging continued until the flood caused by Hurricane Agnes in June 1972. Because the reservoir surveys conducted in 1951, 1959, and 1961 indicated the amount of sediment deposited in Lake Clarke remained about the same, the dredged material was replaced by incoming sediments.

Ledvina (1962) reported results of siltation surveys of Lake Aldred conducted by the Pennsylvania Power and Light Company and the Holtwood Steam Electric Station. These surveys indicate that the annual amounts of sediment deposited in Lake Aldred are variable. Ledvina reported that the lake contained 19.3 million tons of sediment in 1939, 13.3 million tons in 1950, and 9.97 million tons in 1961. Reasons for the decline in sediment were not given, but coal was dredged from the reservoir during most of the period.

Whaley (1960) reported temperature, dissolved oxygen concentrations, velocity distributions, and bottom elevations at six cross-sections in Conowingo Reservoir in 1959. His data indicate that the capacity of Conowingo Reservoir was reduced from 300,000 acre-ft in 1928 to 235,000 acre-ft in 1959. The reservoir contained an estimated 92 million tons of sediment in 1959.

DATA-COLLECTION METHODS

Continuous seismic-reflection profiles were run at about 10 locations in each of the lakes to determine the areal extent and the thickness of sediment deposition. Bottom-material sampling points were selected to characterize the particle size and chemistry of the material deposited in the reservoirs and to confirm the sediment thickness as determined by geophysical techniques. Suspended-sediment samples were collected during periods of high flow from 1984 to 1989 at the Susquehanna River at Marietta, Pa., and from the Conestoga River at Conestoga, Pa. The sediment deposition data were used, along with suspended-sediment transport data, to calibrate and test a model to compute deposition and re-suspension of sediment over a range of flows.

Seismic-Reflection Survey

The continuous seismic-reflection profiling method (Gorin and Haeni, 1988; Wolansky and others, 1982) is based on signals transmitted from a sound source and reflected at air-water, water-sediment, and sediment-rock interfaces. Depths are determined by observing the arrival time of the reflected waves and applying a velocity to the wave. The velocity of sound is related to compressibility and specific weight of the medium through which it travels. The velocity of sound in water is 4,720 ft/s and the velocity in saturated unconsolidated sediments is about 5,000 ft/s. The velocity of sound in bedrock varies but is also greater than velocity of sound in water. The seismic signal penetrates to a depth of 100 ft in fine-grained sediments but is limited to 5 ft in coarse sediments because gravel and larger particles severely scatter the signals. Resolution is 1 to 2 ft. A fathometer, operating at a signal frequency of 192 kilohertz, was also used to provide a record of water depth and morphology of the bottom of each reservoir.

Bottom Material

A total of 54 core samples were collected from the bottom material in the reservoirs from October 1990 to April 1991. The sample-collection sites in each reservoir are listed in table 3. Samples of the bottom material were collected to a maximum depth of 7 ft with a 2-in. diameter stainless-steel core sampler equipped with a plastic liner. Bed-material samples were analyzed for particle-size distribution, percentage of coal, dry density, and concentrations of selected nutrient and metal species. Results of all sample analyses are published in "Water Resources Data for Pennsylvania, Water Year 1991, Volume 2" (Durlin and Schaffstall, 1992).

Table 3. *Site identification number and location of water-quality and bottom-material sampling sites on the Lower Susquehanna River*

[Latitude, in degrees, minutes, seconds north; Longitude in degrees, minutes, seconds west]

Lake Clarke			Lake Aldred			Conowingo Reservoir		
Site number	Latitude	Longitude	Site number	Latitude	Longitude	Site number	Latitude	Longitude
LC 05.01	395738	0762908	LA 01.02	394947	0762008	CO 01.01	393939	0761109
LC 05.06	395757	0762755	LA 03.02	395050	0762101	CO 01.03	393955	0761058
LC 07.02	395624	0762704	LA 03.04	395058	0762045	CO 01.05	394010	0761049
LC 07.03	395635	0762653	LA 04.02	395127	0762133	CO 02.02	394039	0761150
LC 09.03	395538	0762501	LA 04.03	395135	0762125	CO 02.03	394025	0761152
LC 10.01	395457	0762417	LA 06.02	395303	0762219	CO 02.04	394017	0761200
LC 10.02	395518	0762405	LA 06.03	395305	0762231	CO 03.05	394104	0761255
LC 10.03	395529	0762358	LA 12.03	395414	0762241	CO 04.03	394208	0761402
LC 10.04	395542	0762355	LA 12.11	395210	0762226	CO 04.05	394212	0761335
LC 12.01	395756	0762728	LA 12.14	395111	0762108	CO 05.02	394254	0761407
LC 12.03	395822	0762738	LA 12.18	394944	0762023	CO 07.03	394453	0761441
LC 12.05	395904	0762801	LA 13.09	395023	0762057	CO 08.01	394608	0761508
LC 12.07	395931	0762819	LA 13.11	395040	0762059	CO 08.03	394544	0761523
LC 14.07	395701	0762754	LA 13.12	395050	0762105	CO 08.05	394524	0761545
LC 14.09	395620	0762640	LA 15.04	394958	0762035	CO 09.02	394704	0761605
LC 14.10	395550	0762517	LA 15.06	395015	0762047	CO 09.03	394655	0761622
LC 15.02	395550	0762603	LA 15.13	395132	0762158	CO 10.03	394738	0761716
LC 15.06	395627	0762728	LA 15.14	395142	0762218	CO 11.06	394530	0761430
LC 16.03	395546	0762433	LA 16.03	395329	0762247	CO 12.01	394339	0761407
			LA 16.05	395353	0762254	CO 12.05	394148	0761318
			LA 17.03	395341	0762219	CO 12.06	394126	0761258
			LA 17.04	395320	0762218	CO 13.02	394107	0761223
			LA 17.07	395244	0762254	CO 13.05	394007	0761124
			LA 17.09	395220	0762248			
			LA 17.11	395155	0762234			

All chemical analyses were performed at the USGS National Water Quality Laboratory in Arvada, Colo. Bed-material particle-size analyses were performed at the USGS Pennsylvania District Sediment Laboratory in Lemoyne to determine the percentage of sand, silt, clay, and coal. Samples of the bottom material were sieved to determine the weight of sediment that had a diameter of greater than 0.062, 0.125, 0.25, 0.50, 1.00, and 2.00 mm. The percentages of silt and clay were determined by standard particle-size analysis techniques (Guy, 1969).

The percentage of coal by volume of each of the six sieved portions was visually estimated, and then used to estimate the percentage of coal and sand by weight in each sample. The following example demonstrates the method used to determine the percentages of sand and coal by weight in each sieved portion of the sediment samples.

A 0.89 g portion of sediment in the 1.00-2.00 mm class was visually estimated to contain 40 percent coal and 60 percent sand, by volume. Specific gravities of 1.7 for coal and 2.4 for sand were assumed. The relative weights of coal and sand were determined by multiplying the volume estimate by the assumed specific gravity for each particle type.

$$0.40 \times 1.7 = 0.68 \text{ (relative weight of coal in this portion)} \tag{1}$$

$$0.60 \times 2.4 = 1.44 \text{ (relative weight of sand in this portion)} \tag{2}$$

$$0.68 + 1.44 = 2.12 \text{ (total relative weight)} \tag{3}$$

To determine the actual weight of coal and sand in the portion, the ratio of the total actual weight of the sample and the total relative weight was determined.

$$0.89 \text{ g} / 2.12 = 0.42 \text{ (ratio of total actual weight to total relative weight)} \tag{4}$$

The ratio was then multiplied by the relative weights to determine the actual weight of coal and sand in the portion.

$$0.68 \times 0.42 = 0.29 \text{ g (weight of coal in this portion)} \tag{5}$$

$$1.44 \times 0.42 = 0.60 \text{ g (weight of sand in this portion)} \tag{6}$$

The percentages of coal and sand, by weight, in this 1.00-2.00 mm class portion are 33 percent (0.29 g / 0.89 g) and 67 percent (0.60 g / 0.89 g), respectively.

DEPOSITION IN THE LOWER SUSQUEHANNA RIVER RESERVOIR SYSTEM

After the hydroelectric dams were constructed on the Lower Susquehanna River, large amounts of coal and other sand-size particles and some of the silt and clay particles transported by the river were trapped in the reservoirs and no longer reached Chesapeake Bay. The headwaters of the reservoirs generally contain large deposits of sand and coal and the middle and lower parts of the reservoirs contain less sand and coal and more silt and clay.

About 10 percent of the nitrogen trapped in the sediments is ammonia and the rest is organic nitrogen. Together, nitrite and nitrate accounted for less than 0.1 percent of the total nitrogen in each of the impoundments and are not discussed in this report. For this report, concentrations of ammonia and organic nitrogen are expressed as nitrogen (N) and concentrations of phosphorus are expressed as phosphorus (P).

Data from bed-material samples from each of the three impoundments indicated that concentrations of iron were generally 2 to 3 times greater than concentrations of aluminum and 12 to 18 times greater than concentrations of manganese.

Lake Clarke

Sediment Distribution

Sediment deposition in Lake Clarke was greatest in the Lower Lake area and least in the Long Level channel (fig. 3, table 4). The Washington Boro flats, excluding the three large islands, contained about 15,600 acre-ft (723 million ft^3) of sediment. Sediment samples collected in the Washington Boro flats had a dry density of about 71 lb/ft^3, and about 25.7 million tons of sediment were deposited in the flats (table 4). The upstream 3 mi of the bed of the Long Level channel is composed primarily of cobbles and boulders (material with a diameter greater than 64 mm), and few (if any) deposits of fine-grained sediment are present. Sediment deposited in the 520-acre downstream reach of the Long Level channel, from Long Level to Turkey Hill, has an average depth of 3.7 ft, and the area contains about 1,920 acre-ft of sediment (table 4)

The amount of sediment deposited in the Lower Lake subarea of Lake Clarke is about 43,600 acre-ft (1.9 billion ft^3); the density of the sediment is about 65 lb/ft^3, the weight of sediment is calculated to be about 62.0 million tons (table 4). The total weight of sediment in Lake Clarke is about 90.7 million tons..

Table 4. *Estimated sediment deposition and composition for subareas of and for Lake Clarke, Lake Aldred, and Conowingo Reservoir, Lower Susquehanna River Basin, 1990*

Reservoir or Reservoir subarea	Design capacity (acre-feet)	Sediment deposition		Sand (percent)	Silt (percent)	Clay (percent)	Coal (percent)
		(acre-feet)	(tons)				
		Lake Clarke					
Washington Boro flats	24,600	15,600	25,700,000	52	16	10	22
Long Level channel	47,600	1,920	3,000,000	26	43	30	1
Lower Lake	77,800	43,600	62,000,000	18	49	28	5
Lake Clarke	150,000	61,120	90,700,000	28	39	23	10
		Lake Aldred					
Weise Island	4,700	4,130	6,600,000	33	35	15	16
Duncan Island	19,500	3,280	5,200,000	46	21	21	12
Lower Lake Aldred	20,500	1,170	1,800,000	31	28	21	20
Lake Aldred	60,000	8,580	13,600,000	38	29	18	15
		Conowingo Reservoir					
Mt. Johnson Island	41,000	7,120	11,000,000	45	18	7	30
Middle Reservoir	114,000	41,100	63,400,000	39	36	18	7
Lower Reservoir	145,000	56,700	80,500,000	5	58	35	2
Conowingo Reservoir	300,000	104,920	155,000,000	22	46	26	6

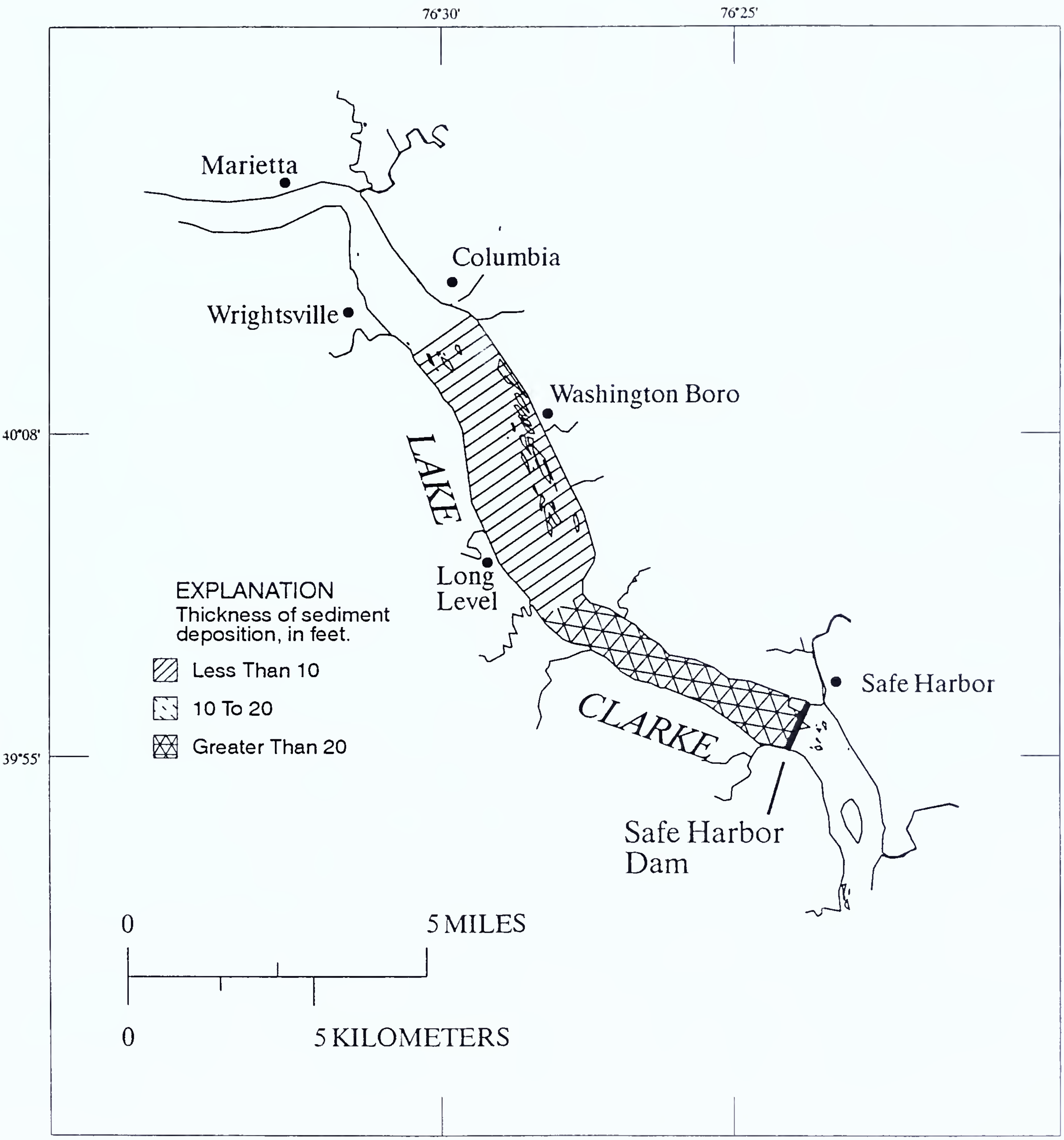


Figure 3. The thickness of sediment deposition in Lake Clarke.

Particle size and coal percentages

In Lake Clarke, the percentage of sand ranged from 52 percent in the Washington Boro flats to 18 percent in Lower Lake (table 4). The average of all samples in Lake Clarke was 28 percent. Silt averaged 39 percent and clay averaged 23 percent. About 10 percent of the sediment deposits was coal. The highest percentage of coal—22 percent—was in samples from Washington Boro flats. Elsewhere in Lake Clarke, 5 percent or less of coal was found. Averaged estimates of the percentage of clay in the sediments deposited in all three reservoirs are shown on figure 4.

Nutrients

The concentration of ammonia in sediments deposited in the reservoirs appears to be related to the particle size of the bottom material. The concentration of ammonia in the sediments deposited in the Washington Boro flats subarea of Lake Clarke averaged 175 mg/kg, the lowest concentrations in the lake (table 5). This area also had the smallest percentage of silt and clay of any area in the lake, 26 percent (table 4). Sediments deposited in Lower Lake, above Safe Harbor Dam, contained an average ammonia concentration of 456 mg/kg. Sediments in this area contained an average of 77 percent silt and clay (table 4). The total quantity of ammonia in sediment in Lake Clarke was calculated at 34,100 tons, and the average concentration was 376 mg/kg (table 5).

Table 5. *Mean concentrations and deposition of ammonia, organic nitrogen, phosphorus, iron, aluminum, and manganese in subareas of and in Lake Clarke, Lake Aldred, and Conowingo Reservoir, Lower Susquehanna River Basin*

[mg/kg, milligram per kilogram]

Reservoir subarea	Ammonia as N		Organic nitrogen as N		Phosphorus as P		Iron as Fe		Aluminum		Manganese	
	mg/kg	tons	mg/kg	tons	mg/kg	tons	mg/kg	tons	mg/kg	tons	mg/kg	tons
Lake Clarke												
Washington Boro flats	175	4,500	3,710	95,300	490	12,600	15,200	391,000	4,010	103,000	990	25,400
Long Level channel	433	1,300	2,670	8,000	1,000	3,000	13,000	39,000	5,400	16,200	1,400	4,200
Lower Lake	456	28,300	3,330	206,000	970	60,100	18,900	1,170,000	6,870	426,000	1,800	112,000
Lake Clarke	376	34,100	3,410	309,000	835	75,700	17,600	1,600,000	6,010	545,000	1,560	142,000
Lake Aldred												
Weise Island	212	1,400	2,580	17,000	710	4,700	19,200	127,000	9,080	59,900	1,060	7,010
Duncan Island	58	300	2,380	12,400	470	2,440	11,700	61,000	4,690	24,400	580	3,000
Lower Lake Aldred	277	500	4,320	7,780	640	1,150	18,000	32,400	7,280	13,100	1,200	2,160
Lake Aldred	162	2,200	2,740	37,200	610	8,290	16,200	220,000	7,160	97,400	900	12,200
Conowingo Reservoir												
Mt. Johnson Island	173	1,900	3,440	37,900	600	6,600	28,000	308,000	9,730	107,000	1,200	13,200
Middle Reservoir	230	14,600	2,960	188,000	750	47,500	27,000	1,710,000	10,800	685,000	1,400	88,800
Lower Reservoir	573	46,100	3,010	242,000	1,100	88,400	22,000	1,770,000	10,200	819,000	1,910	153,000
Conowingo Reservoir	404	62,600	3,020	468,000	920	142,000	24,400	3,790,000	10,400	1,610,000	1,650	255,000

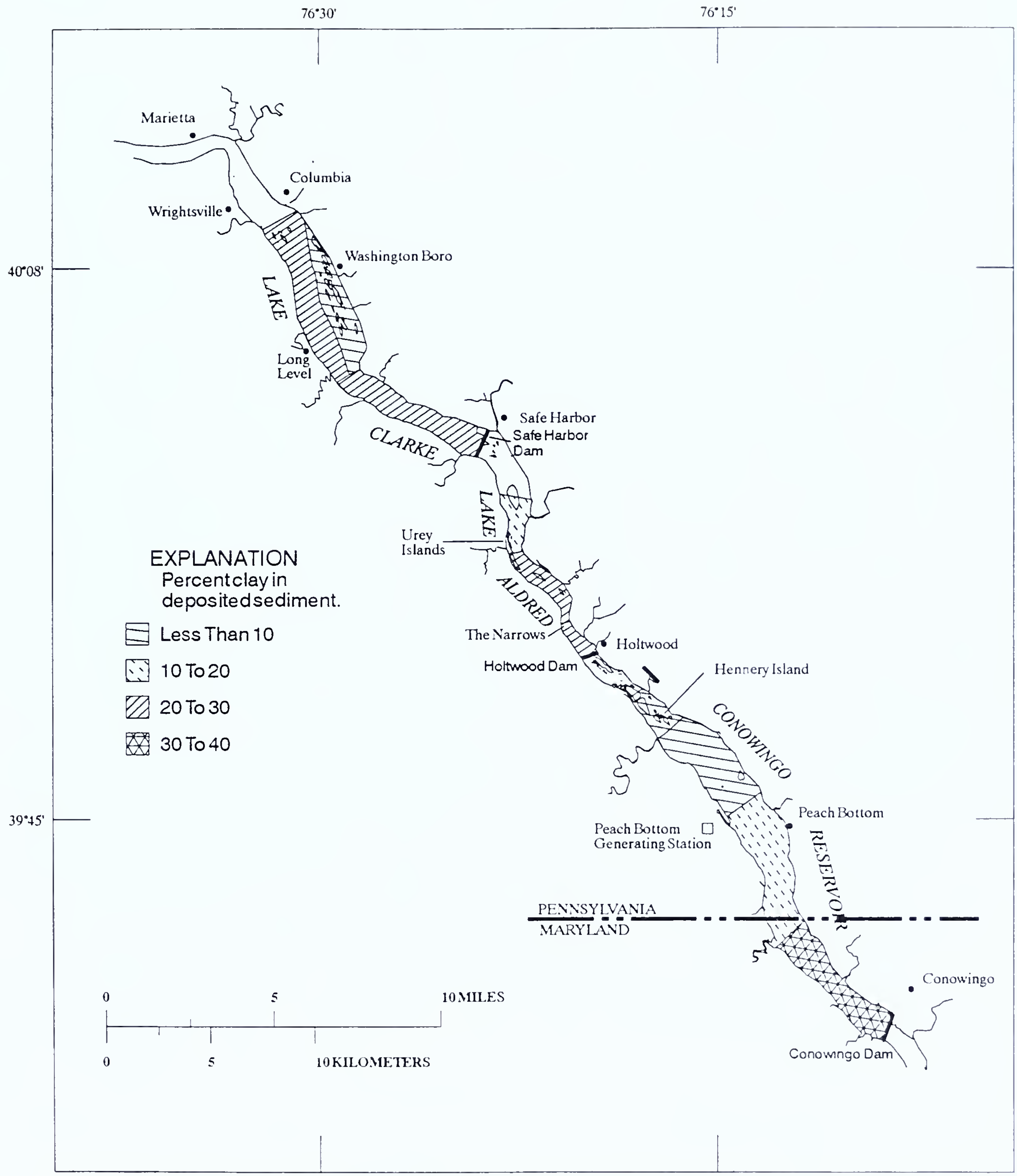


Figure 4. The percentage of clay in the sediment deposited in the three reservoirs on the Lower Susquehanna River.

Ranges of concentrations of organic nitrogen in the sediments deposited in all three reservoirs are shown in figure 5. Lake Clarke contained 309,000 tons of organic nitrogen, and the average concentration was 3,410 mg/kg (table 5). Concentrations of organic nitrogen in the sediments deposited in Lake Clarke ranged from 3,710 mg/kg in the Washington Boro flats to 2,670 mg/kg in the Long Level channel subarea.

Similar to ammonia, the concentration of phosphorus in the sediments deposited in the reservoirs was generally greater in areas where the sediment was mostly silt and clay. Concentration ranges of phosphorus in the sediments deposited in Lake Clarke and the other two reservoirs are shown in figure 6.

Concentrations of phosphorus in the Washington Boro flats section of Lake Clarke averaged 490 mg/kg. Phosphorus concentrations were highest in Lower Lake; phosphorus concentrations in this section averaged 970 mg/kg. Sediments in Lake Clarke contained 75,700 tons of phosphorus, and the average concentration was 835 mg/kg.

Metals

Concentrations of each metal were of the same magnitude in all three areas of Lake Clarke, but because the Lower Lake area contains substantially more sediment than the other areas, it contained the greatest quantity of metals (table 5).

Iron deposition in Lake Clarke totaled 1,600,000 tons, and the average concentration in the sediments was 17,600 mg/kg (table 5). Concentrations of iron in the sediment deposited in the Washington Boro flats subarea of Lake Clarke averaged 15,200 mg/kg, and the sediment contained 391,000 tons of iron. Concentrations of iron in the sediments in the Lower Lake subarea averaged 18,900 mg/kg, and the sediment contained 1,170,000 tons of iron.

Concentrations of aluminum in the sediment collected from Lake Clarke averaged 6,010 mg/kg, and the total quantity of aluminum was calculated at 545,000 tons (table 5). Aluminum concentrations in the sediments deposited in the Washington Boro flats subarea of Lake Clarke averaged 4,010 mg/kg, and the subarea contained 103,000 tons of aluminum. Aluminum concentrations in the sediments in the Lower Lake subarea above the dam averaged 6,870 mg/kg and the area contained 426,000 tons of aluminum.

In Lake Clarke, the average concentration of manganese in the sediment deposited in the Washington Boro flats, 990 mg/kg, was about half the concentration in the sediment deposited in the Lower Lake, 1,800 mg/kg (table 5). Sediment in the Washington Boro flats contained 25,400 tons of manganese, the Lower Lake subarea contained 112,000 tons, and total manganese deposition in Lake Clarke was 142,000 tons.

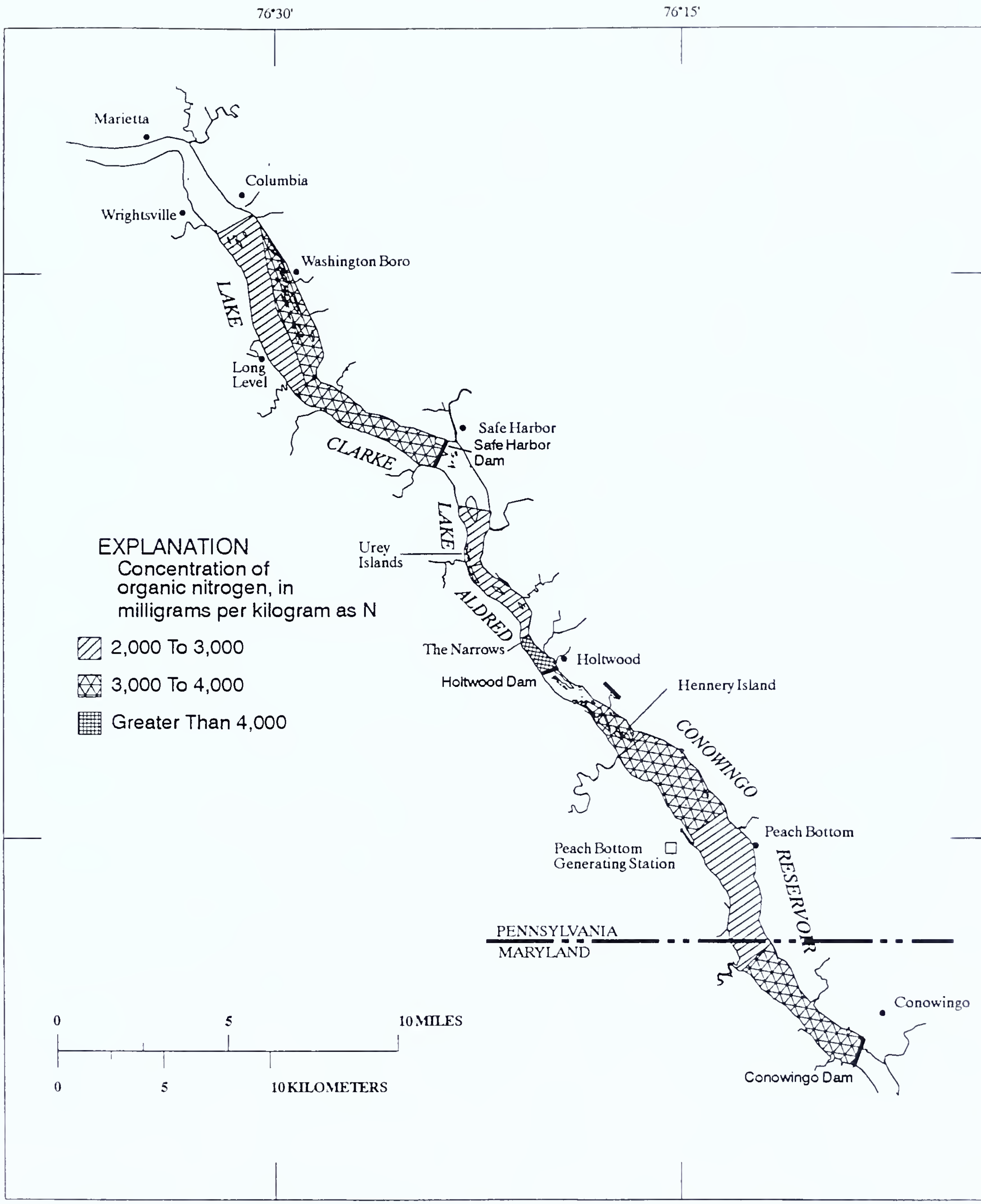


Figure 5. Concentration ranges of organic nitrogen in the sediment deposited in the three reservoirs on the Lower Susquehanna River.

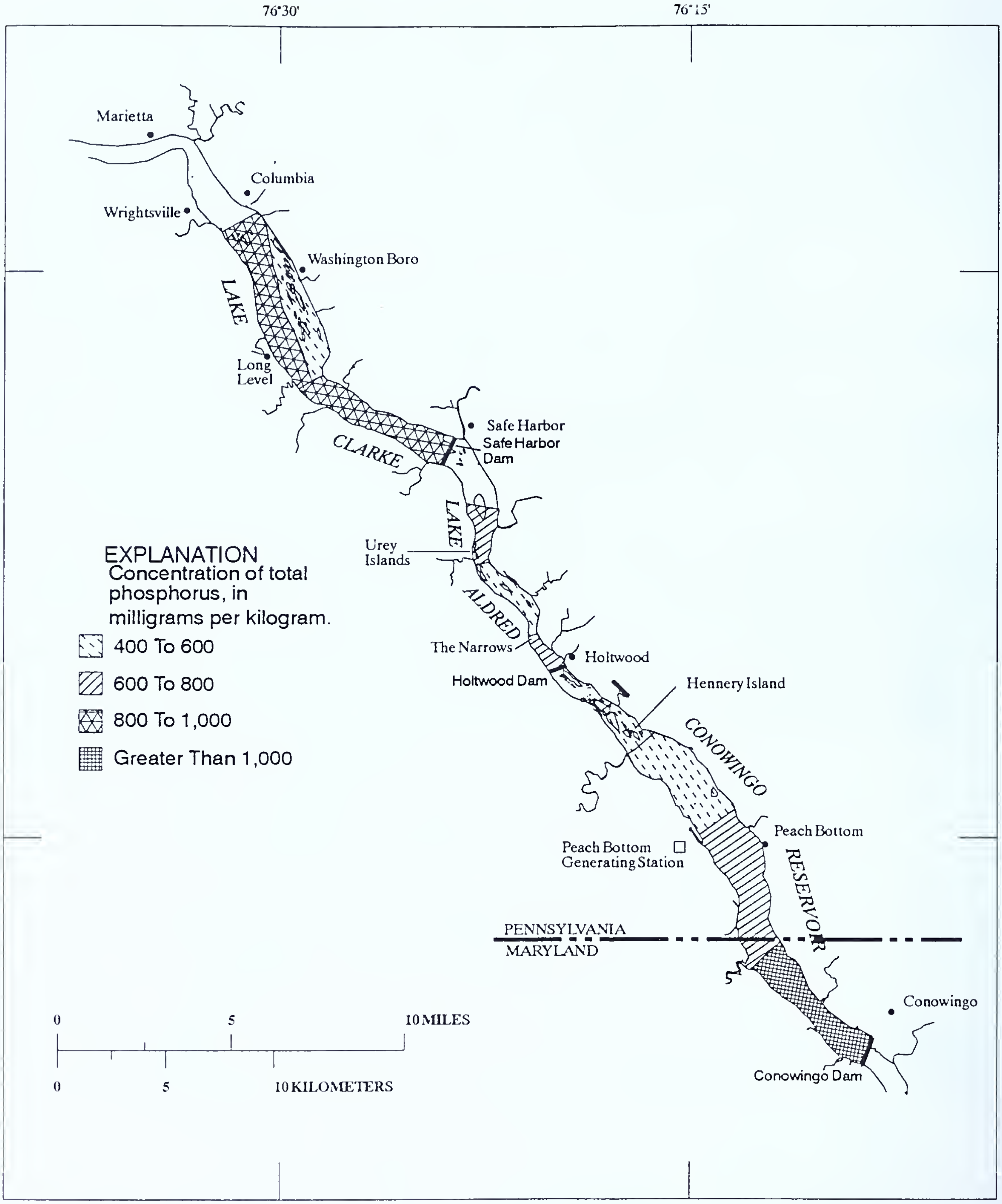


Figure 6. Concentration ranges of phosphorus in the sediment deposited in the three reservoirs on the Lower Susquehanna River.

Lake Aldred

Sediment Distribution

Sediment thickness in Lake Aldred is estimated to be less than 10 ft throughout the lake. The most upstream area of Lake Aldred, the area just downstream of Safe Harbor Dam, had little or no sediment deposition. About 4,130 acre-ft (180 million ft^3) of sediment were deposited in the 660-acre Weise Island area; the dry weight of this sediment was about 6.6 million tons (table 4). The 830-acre Duncan Island area contained about 3,280 acre-ft (143 million ft^3) of sediment and the dry weight was about 5.2 million tons. The 290-acre Lower Lake Aldred area contained about 1,170 acre-ft (50.8 million ft^3) of sediment and the dry weight of the sediment was about 1.8 million tons. Total sediment deposition in Lake Aldred was 13.6 million tons.

Sediment Composition

Particle size and coal percentage

The percentages of sand, silt, clay, and coal in bottom-material samples collected from each of the subareas in Lake Aldred are summarized in table 4. The percentages for these samples were less variable than those in Lake Clarke. Sand content was highest in the Duncan Island area. The percentage of sand ranged from 31 to 46 and averaged 38 percent. Clay and coal averaged about 18 and 15 percent, respectively.

Nutrients

In Lake Aldred, the maximum concentration of ammonia, 470 mg/kg, was in a bed sample collected from a channel west of the Urey Islands (fig. 2). The average concentration in the Weise Island subarea was 212 mg/kg, and the deposition of ammonia was 1,400 tons (table 5). Concentrations of ammonia in the Duncan Island subarea were the lowest in the lake, 58 mg/kg, and the deposition of ammonia was only 300 tons. In Lower Lake Aldred, concentrations of ammonia increased from the Narrows toward the Holtwood Dam. The average concentration of ammonia in the sediment in Lower Lake Aldred was 277 mg/kg, and 500 tons of ammonia were deposited in the sediment. The average concentration of ammonia in all the samples from Lake Aldred was 162 mg/kg, and 2,200 tons of ammonia were deposited in the lake.

The greatest average concentration of organic nitrogen in sediments from the three reservoirs was from Lower Lake Aldred (fig. 5, table 5). Lake Aldred contained 37,200 tons of organic nitrogen. Concentrations averaged 2,580 mg/kg in the Weise Island subarea, 2,380 mg/kg in the Duncan Island subarea, and 4,320 mg/kg in the Lower Lake Aldred subarea.

Phosphorus concentrations in the sediments deposited in the Weise Island subarea, the Duncan Island subarea, and the Lower Lake Aldred subarea averaged 710, 470, and 640 mg/kg, respectively (fig. 6, table 5). Total phosphorus deposition in Lake Aldred was 8,290 tons.

Metals

In Lake Aldred, the concentration of iron in the sediments deposited in the Weise Island subarea, in the Duncan Island subarea, and in the Lower Lake Aldred subarea averaged 19,200, 11,700, and 18,000 mg/kg, respectively (table 5). The average concentration of iron in the sediments in Lake Aldred was 16,200 mg/kg, and the lake contained 220,000 tons of iron.

Concentrations of aluminum in the sediment deposited in Lake Aldred are shown in figure 7. The highest average concentration of aluminum in the sediment (9,080 mg/kg) was in the Weise Island subarea. The subarea contained 59,900 tons of aluminum. Total aluminum deposition in Lake Aldred was 97,400 tons, and the average concentration was 7,160 mg/kg.

Average concentrations of manganese ranged from 580 mg/kg in sediments deposited in the Duncan Island subarea to 1,200 mg/kg in the sediments above the Holtwood Dam. Lake Aldred contained 12,200 tons of manganese, and the average concentration was 900 mg/kg.

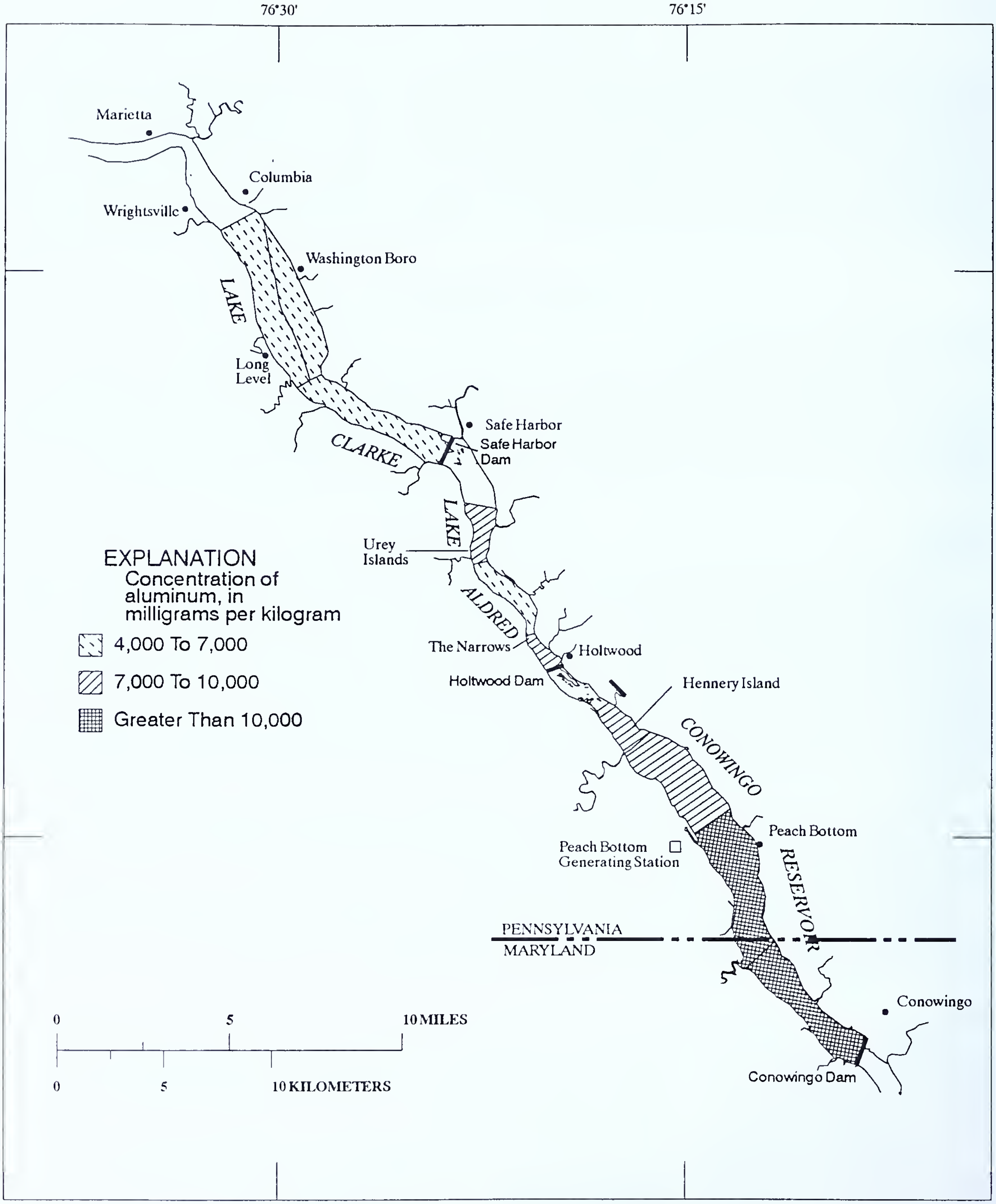


Figure 7. Concentration ranges of aluminum in the sediment deposited in the three reservoirs on the Lower Susquehanna River.

Conowingo Reservoir

Sediment Distribution

The Conowingo Reservoir contains more sediment than the other two reservoirs combined. Sediment deposition in the three reservoirs totaled 259 million tons, of which 155 million tons was in Conowingo Reservoir (table 4). Sediment thickness was least in the Mt. Johnson Island subarea and ranged from zero in the upper reaches near Hennery Island to 5 ft in the middle and lower areas of the reservoir (fig. 8). Sediment deposition in the Mt. Johnson Island subarea was about 7,120 acre-ft (310 million ft^3), the average depth was 3.1 ft, and the dry weight of the deposited sediment was about 11 million tons. Sediment deposition in the 3,020-acre Middle Reservoir area was 41,100 acre-ft (1.79 billion ft^3) and had an average thickness of 13.6 ft. The dry weight of the sediment was about 63.4 million tons. Sediment was thickest in the Lower Reservoir area, which had an average thickness of about 30 ft. The volume of the sediment in this area was about 56,700 acre-ft (2.47 billion ft^3). The dry weight of the sediment was 80.5 million tons.

Sediment Composition

Particle size and coal percentage

Steep gradients of sand and clay composition were measured in the Conowingo Reservoir. About 45 percent of the sediment deposited in the Mt. Johnson Island subarea was sand; in the Lower Reservoir area, immediately above Conowingo Dam, the sediment was only about 5 percent sand (table 4). About 7 percent of the sediment was clay at the upper end, and 35 percent was clay above the dam. Coal ranged from 2 to 30 percent throughout the reservoir.

Nutrients

Concentrations of ammonia in samples collected from the Conowingo Reservoir ranged from 13 mg/kg in a sample collected in the Mt. Johnson Island subarea to 730 mg/kg in a sample collected near the Conowingo Dam. The average concentration of ammonia in the sediment deposited in the Mt. Johnson Island subarea was 173 mg/kg, and the area contained 1,900 tons of ammonia (table 5). Sediment in the Mt. Johnson area averaged 25 percent silt and clay. The average concentration of ammonia in the sediments deposited in the Middle Reservoir area was 230 mg/kg, and the subarea contained 14,600 tons of ammonia. The average concentration in the Lower Reservoir subarea, just above Conowingo Dam, was 573 mg/kg, and the area contained 46,100 tons of ammonia. Silt and clay made up 93 percent of the sediment in the Lower Reservoir area above Conowingo Dam. The total ammonia deposition in the sediments in Conowingo Reservoir was 62,600 tons (table 5). About 63 percent of the total ammonia deposition in the three reservoirs (98,900 tons) was stored in Conowingo Reservoir. The average concentration in the three reservoirs was 381 mg/kg.

Concentrations of organic nitrogen in the sediments deposited in Conowingo Reservoir are shown in figure 5. The average concentrations of the three subareas had little variation (table 5). Average concentrations were 3,440 mg/kg in the Mt. Johnson Island subarea, and the subarea contained 37,900 tons of organic nitrogen. Concentrations in the Middle Reservoir area averaged 2,960 mg/kg, and the subarea contained 188,000 tons of organic nitrogen. The Lower Reservoir area contained the most organic nitrogen, 242,000 tons, and the average concentration was 3,010 mg/kg. The three reservoirs contained 814,000 tons of organic nitrogen, and the average concentration in the sediments was 3,140 mg/kg.

Sediments deposited in the Mt. Johnson Island subarea had an average concentration of phosphorus of 600 mg/kg (table 5) and the sediment content was 25 percent silt and clay (table 4). Phosphorus concentrations in the Middle Reservoir area averaged 750 mg/kg, and concentrations in the Lower Reservoir area averaged 1,100 mg/kg. Concentrations of phosphorus measured in the sediments deposited in Conowingo Reservoir are shown in figure 6. The sediments contained 142,000 tons of phosphorus and the average concentration of phosphorus was 920 mg/kg. About 226,000 tons of phosphorus was deposited in the three reservoirs and the average concentration was 873 mg/kg.

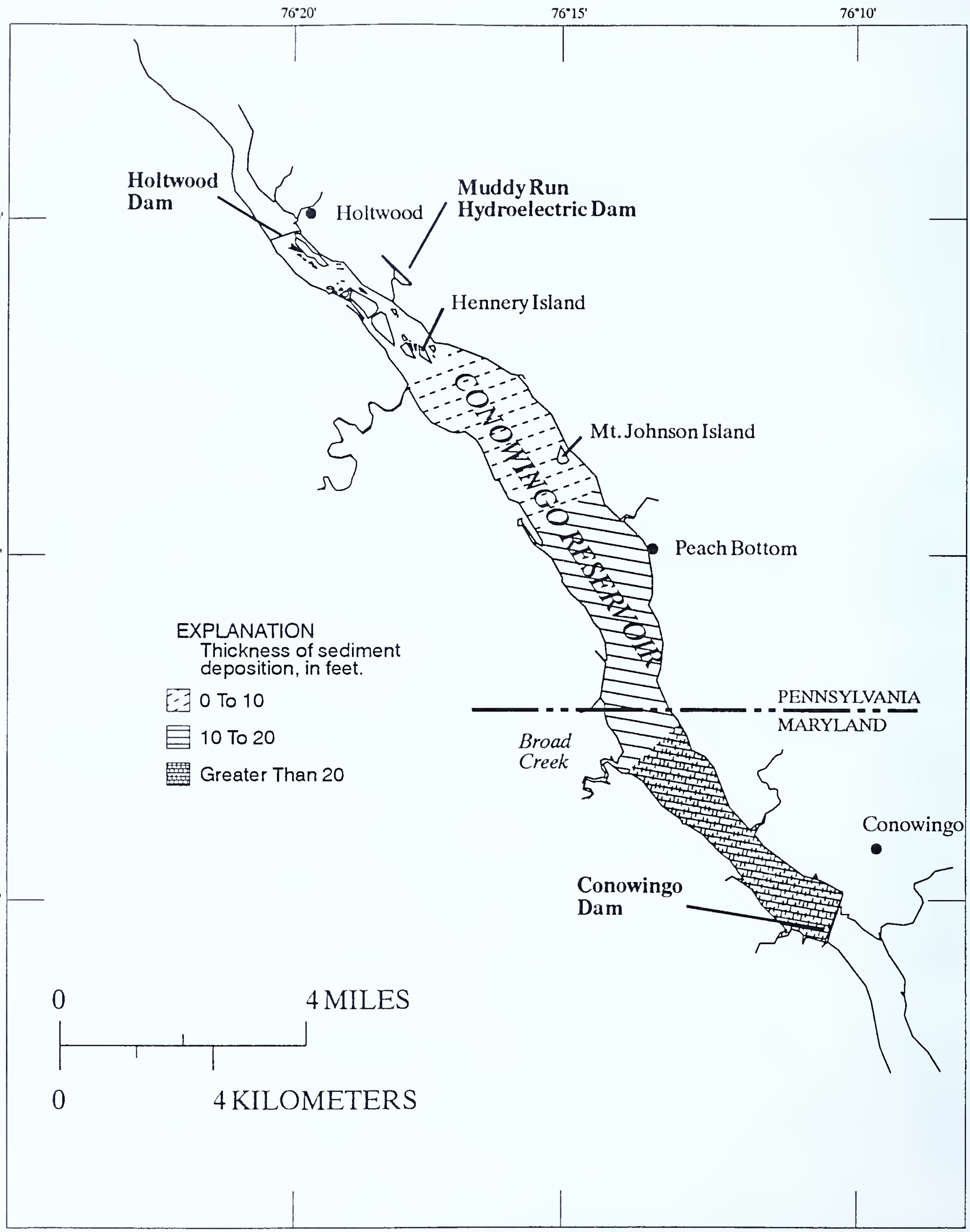


Figure 8. The thickness of sediment deposition in Conowingo Reservoir.

Metals

Concentrations of iron in sediment deposited in Conowingo Reservoir were higher than those in sediment deposited in the other two reservoirs (table 5). The average concentration of iron in the Mt. Johnson Island subarea was 28,000 mg/kg, the average concentration in the Middle Reservoir area was 27,000 mg/kg, and the average concentration in the Lower Reservoir area, just above the Conowingo Dam, was 22,000 mg/kg. The largest concentration, 37,000 mg/kg, was measured in sediment deposited north of Mt. Johnson Island. The average concentration of iron in Conowingo Reservoir was 24,400 mg/kg, and the reservoir contained 3.79 million tons of iron. The three reservoirs contained 5.61 million tons of iron, and the average concentration was 21,600 mg/kg.

Concentration ranges of aluminum in the sediment deposited in the three reservoirs are shown in figure 7. Average concentrations of aluminum in sediment deposited in the three subareas of Conowingo Reservoir ranged from 9,730 mg/kg in the subarea around Mt. Johnson Island to 10,800 mg/kg in the Middle Reservoir area (table 5). Concentrations of aluminum in sediments deposited in the Lower Reservoir subarea of the lake averaged 10,200 mg/kg. The reservoir contained 1,610,000 tons of aluminum; 107,000 tons in the subarea around Mt. Johnson Island, 685,000 tons in the Middle Reservoir area, and 819,000 tons in the Lower Reservoir area. Total aluminum deposition in the three reservoirs was 2,250,000 tons, and the average concentration was 8,700 mg/kg.

Average concentrations of manganese in the sediments deposited in the Conowingo Reservoir ranged from 1,200 mg/kg in the Mt. Johnson Island subarea to 1,910 mg/kg in the area above Conowingo Dam (table 5). Manganese deposition was 13,200 tons in the Mt. Johnson Island subarea, 88,800 tons in the Middle Reservoir area, and 153,000 tons in the Lower Reservoir area. The load of manganese deposited in Conowingo Reservoir was 255,000 tons, and the average concentration of manganese in the sediments was 1,650 mg/kg. Total manganese deposition in the three reservoirs was 409,000 tons, and the average concentration was 1,580 mg/kg.

Effect of Deposition on Reservoir Storage

The reservoirs formed by the dams act as a sediment trap, reducing the load of sediment, nutrients, and metals that would otherwise be transported to Chesapeake Bay. As the reservoirs fill with sediment, the amount of sediment deposited decreases, and the amount transported to the bay increases. Transport to the bay can also be increased during periods of very high flow, when previously deposited materials can be scoured from the reservoirs and transported to Chesapeake Bay.

Lake Clarke

Lake Clarke was surveyed in 1931, 1939, several times from 1940 to 1964, and in 1990. The reservoir water-storage capacity calculated from the survey data is shown in figure 9 . The capacity decreased at an average rate of about 3,400 acre-ft per year for the first 19 years. Since 1950, the capacity of the reservoir has been almost constant.

The average cross-section bed elevations of Lake Clarke in 1931 and in 1990 and the cross-sectional area in the lake for the same years are shown in figure 10. The cross-sectional area of Lake Clarke ranges from about 75,000 to 110,000 ft^2. From 1954 to 1972, about 1.0 million tons of sand and coal per year were dredged from the reservoir. The surveys indicate that the dredged material was replaced by incoming sediments.

Lake Aldred

Average cross-section bed elevations and areas of Lake Aldred have changed little since the construction of Holtwood Dam in 1910 (fig. 11). This indicates that the reservoir reached equilibrium soon after construction, with respect to sediment deposition.

Over the long term (1910-90), sediment deposition in Lake Aldred decreased the cross-sectional area only slightly (fig. 11). Holtwood Dam has no flood gates and river flow in excess of plant capacity is spilled over the breast of the dam. At river discharges where reservoir sediments are expected to scour (400,000 ft^3/s), the increase from the normal pool elevation in Lake Aldred is about 15 ft.

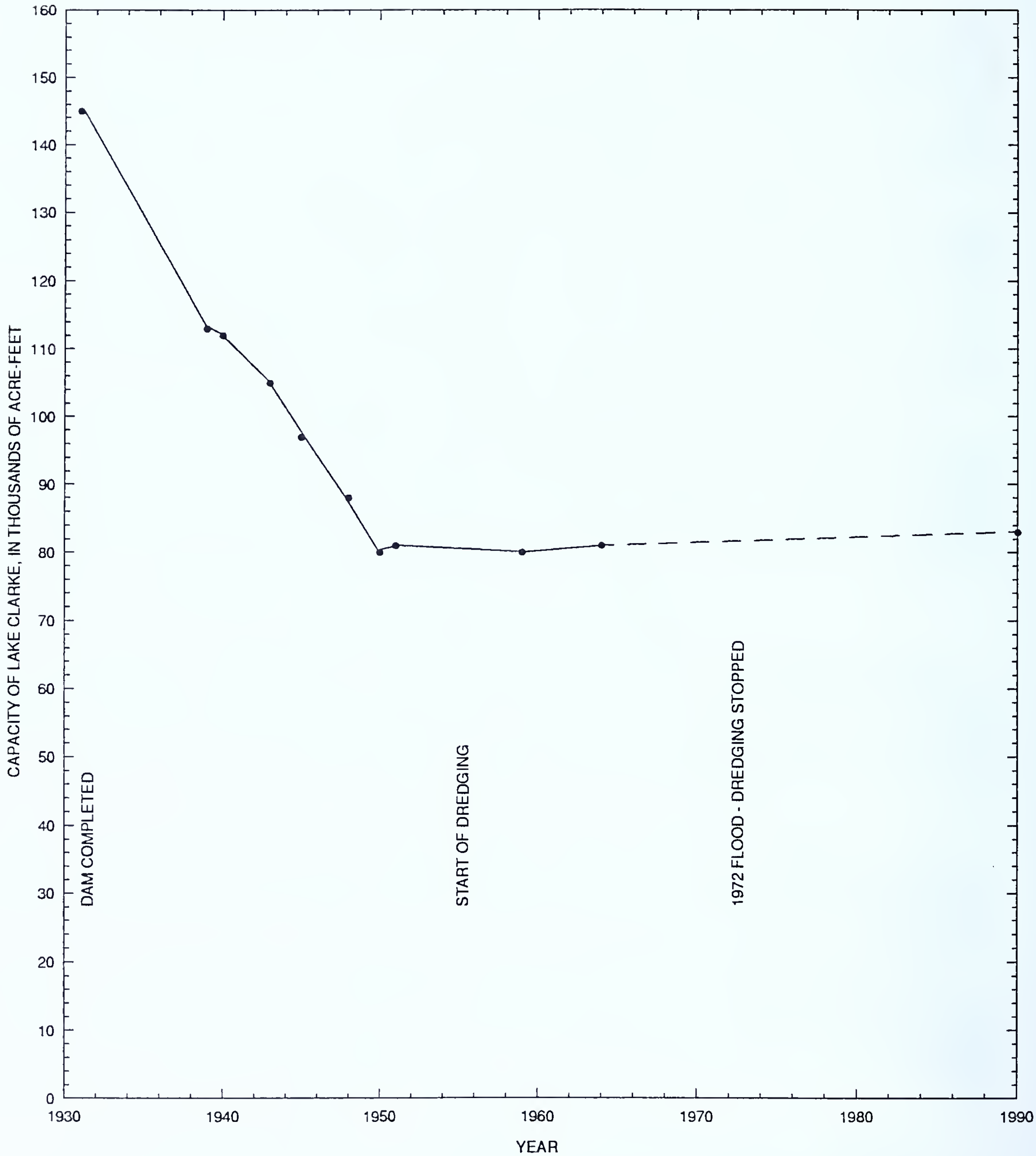
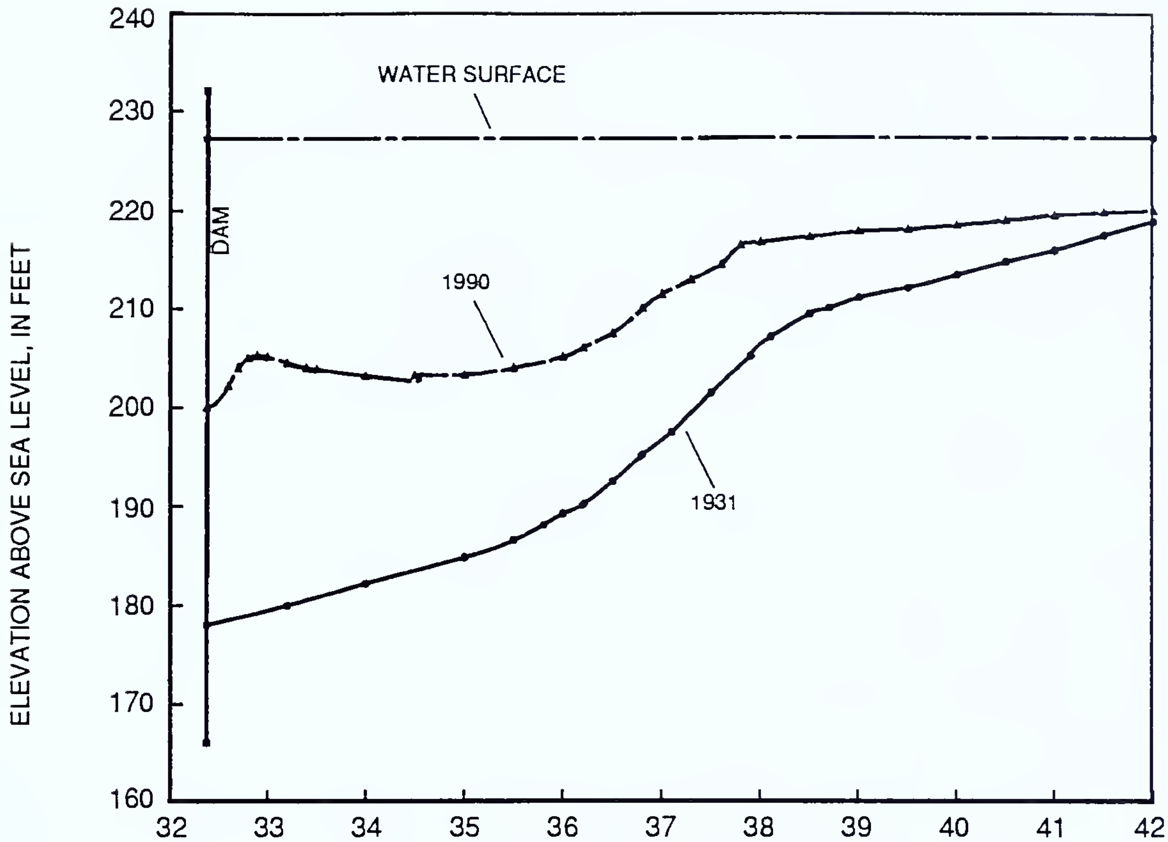


Figure 9. Water-storage capacity of Lake Clarke, Lower Susquehanna River Basin, from the time the Safe Harbor Dam was completed in 1931 through 1990.



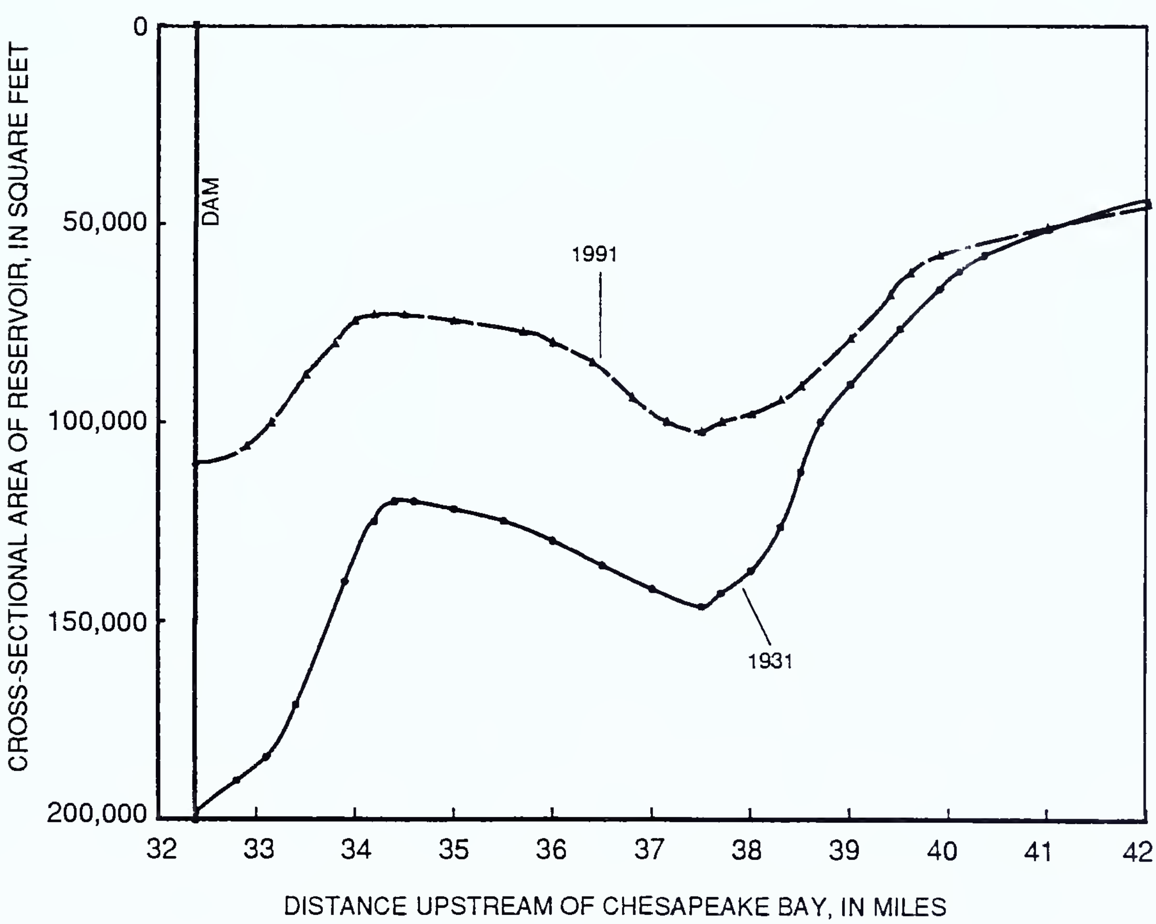


Figure 10. Relations of upstream distance from Chesapeake Bay to average bed elevations and cross-sectional areas in Lake Clarke, Lower Susquehanna River Basin, 1931 and 1990.

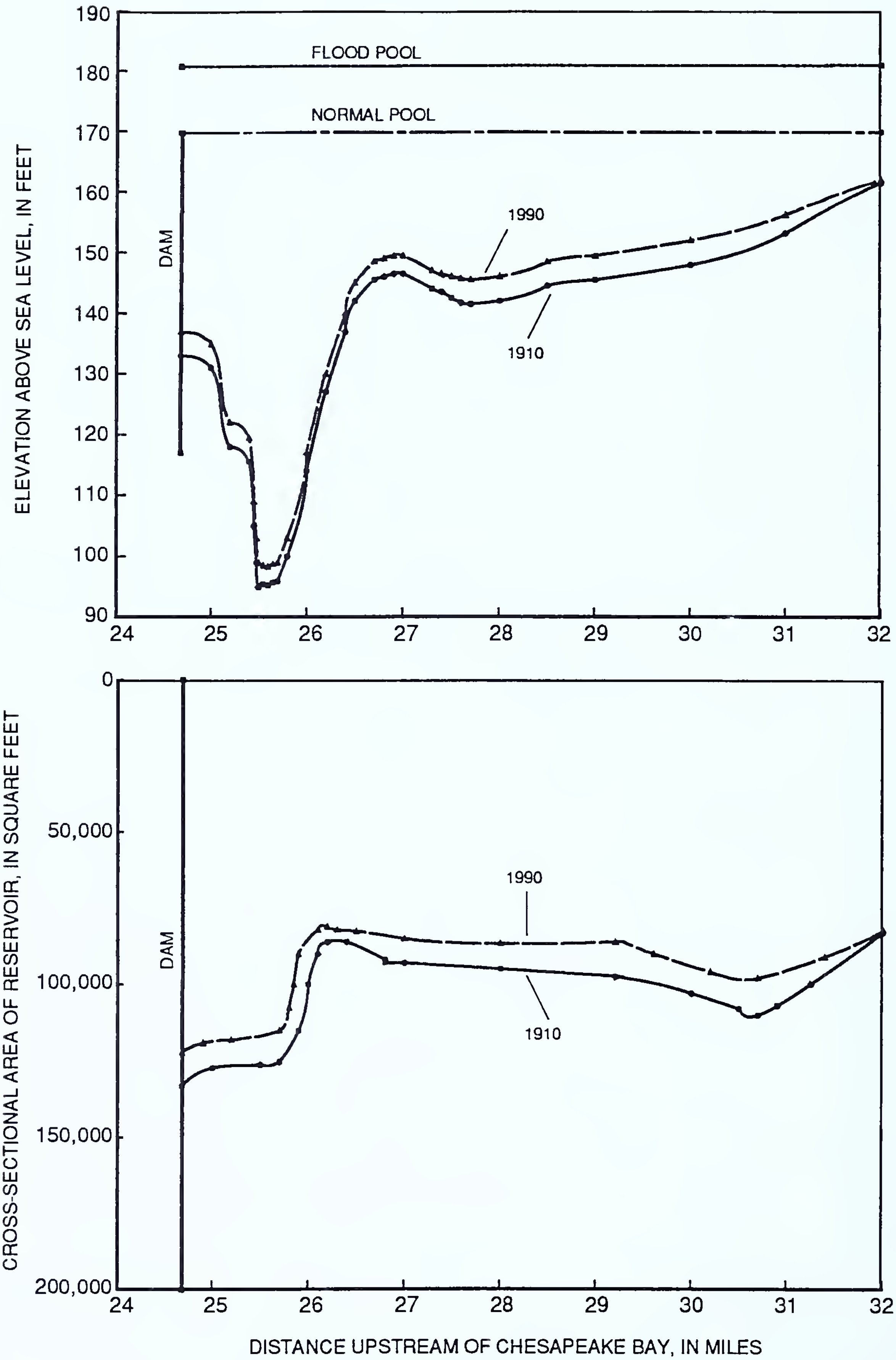


Figure 11. Relations of upstream distance from Chesapeake Bay to average bed elevations and cross-sectional areas in Lake Aldred, Lower Susquehanna River Basin, 1910 and 1990.

Conowingo Reservoir

The capacity of Conowingo Reservoir was 300,000 acre-ft when the dam was completed in 1928. Bottom-elevation data reported by Whaley (1960) indicated that the capacity of the reservoir was about 235,000 acre-ft in 1959. The 1990 survey indicated that the capacity of Conowingo Reservoir was about 196,000 acre-ft.

Although the reservoir has filled considerably since 1959 (fig. 12), bed elevations in the upper third of the reservoir were lower in 1990 than in 1959, indicating that the area has been scoured. The reason for the lowering of bed elevations between 1959 and 1990 may have been the installation of a pump-storage generating station in the headwaters of the reservoir in 1968. Station operations increased the maximum daily instantaneous water discharge in the headwaters of the reservoir from about 27,000 ft^3/s to about 57,000 ft^3/s.

Cross-sectional areas between river miles 15 and 22 range from about 70,000 to 125,000 ft^2, similar to the cross-sectional areas in Lake Clarke and Lake Aldred. It appears that each of the reservoirs in the system reaches equilibrium with respect to sediment when cross-sectional areas are in the range of 70,000 to 125,000 ft^2, or an average area of 100,000 ft^2. The turbulence caused by the bottom-release mechanism at Conowingo Dam will probably not allow as much deposition in the lower subarea of the reservoir as has taken place in upstream subareas and reservoirs. For the purposes of this analysis, a cross-sectional area for equilibrium just above Conowingo Dam was estimated to be 200,000 ft^2. It is assumed that the effect of releases from the dam would diminish with distance upstream from the dam and that the average equilibrium cross-sectional area would eventually approach 100,000 ft^2. On the basis of 1990 cross-sectional data, this was estimated to take place at a point about 1.25 mi upstream of the dam (river mile 11).

On the cross-sectional area graph in figure 12, an additional dashed line is shown. The line is drawn from the dam at a cross-sectional area of 200,000 ft^2 to the estimated reservoir-system equilibrium cross-sectional area of 100,000 ft^2 at a point 1.25 mi upstream of the dam. The reservoir can store an additional 34,000 acre-ft of sediment before the downstream section reaches equilibrium with incoming sediments at the level shown by the dashed line in figure 12.

Suspended-sediment data, collected from the Susquehanna River at Harrisburg and Conowingo and at four major tributaries from 1985 through 1989, were used to calculate sediment deposition in the reservoirs for the 5-year period. Over the 5-year period, a total of 12.6 million tons of sediment was transported to the reservoirs, and the total sediment discharge from Conowingo Reservoir was 3.5 million tons. This indicates that an average of 1.8 million tons of sediment were trapped each year, primarily in the Conowingo Reservoir. Assuming the dry density of the sediment is 65 lb/ft^3, the capacity of the reservoir was decreasing at an average rate of 1,270 acre-ft per year. Water discharge was relatively low during 2 years, 1985 and 1988, and for those years, the average loss of capacity was 770 acre-ft per year. Deposition averaged 1,600 acre-ft per year during the remaining 3 years when water discharge averaged 5 percent below normal. Assuming annual sediment deposition of 1,700 acre-ft, no scour from very large storms, and deposition only in the Conowingo Reservoir, about 20 years would be required to accumulate 34,100 acre-ft in the Conowingo Reservoir.

Even though the exact cross-sectional areas for sediment equilibrium in Conowingo Reservoir are not known, figure 12 shows that the reservoir is nearing capacity and that it will be full in the next 20 or 30 years. Once equilibrium is reached, the incoming loads of sediment and nutrients to the reservoirs will pass through the reservoirs and enter Chesapeake Bay. Loads discharged during periods of high flow will increase, which is routine in the late winter and early spring, and additional loads may be discharged because of scour during extreme flow periods.

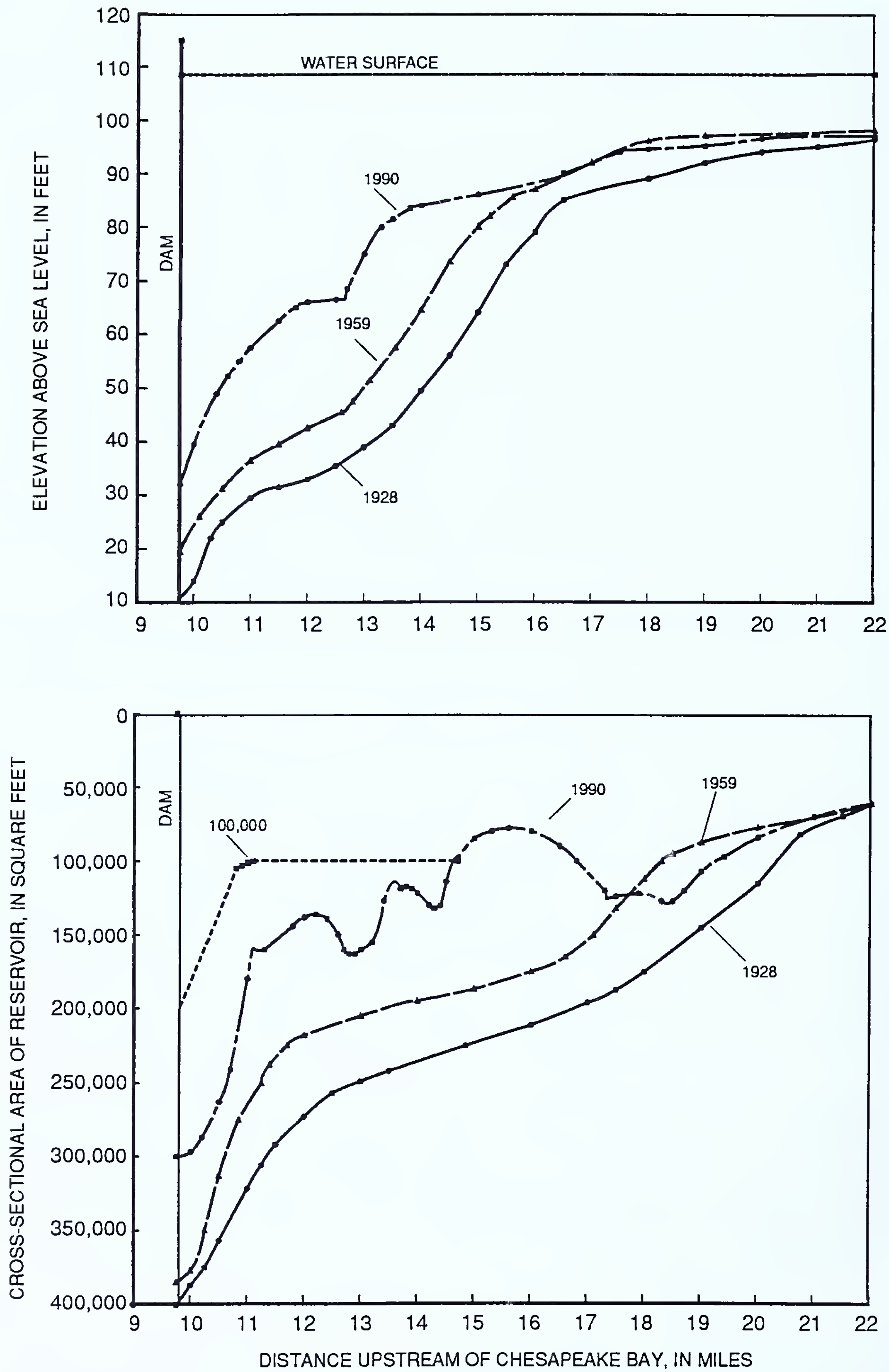


Figure 12. Relations of upstream distance from Chesapeake Bay to average bed elevations and cross-sectional areas in Conowingo Reservoir, Lower Susquehanna River Basin, 1928, 1959, and 1990.

SIMULATION OF SEDIMENT TRANSPORT IN THE RESERVOIR SYSTEM

Description of the Selected Model

A realistic computation of the transport of sediment through large, shallow reservoirs, such as on the Lower Susquehanna River, requires a numerical model that can simulate both the hydraulic characteristics of the stream and the deposition and scour of different sizes of sediment particles. Summaries of the basic equations, functional capabilities, limitations, and available documentation for 12 of the most sophisticated stream-sedimentation models commonly used in the United States (Fan, 1988) were reviewed. The U.S. Army Corps of Engineers' HEC-6 computer model was selected as the most suitable for this study.

The HEC-6 model is designed for one-dimensional simulation of sediment transport under changing conditions of boundary geometry and roughness. Water discharge was assumed to be relatively constant between reservoir sections. Features that were paramount in the selection were the ability to simulate long-term trends of deposition and scour; scour routines that accommodate the full range of grain sizes observed in the inflow; and computation of sediment transport by grain-size fractions, wherein the algorithms accommodate hydraulic sorting and bed armoring.

Limitations of the HEC-6 model include the inability to simulate density currents, bed forms, or lateral gradations in deposition or scour. The coding of inflows, which is composed of a series of short-duration discharge values that approximate the inflow hydrograph, is cumbersome. Sediment-discharge data for outflows must be extracted from the output file and post-processed with auxiliary software to summarize them as daily-value sequences. Sediment-transport capacity is assumed to be in equilibrium with flow hydraulics for each inflow time step, which is a condition that seldom exists in reservoirs during high-flow periods.

The developers of the HEC-6 model recognized that deficiencies in available engineering knowledge limited their ability to write routines for exact simulation of the mechanisms of armoring, hydraulic sorting, and re-entrainment. Of particular significance was the lack of knowledge on the mechanisms of clay transport for concentrations greater than 300 mg/L. Details on the theory, equations, and assumptions incorporated in the HEC-6 model are provided in the "User's Manual" (U.S. Army Corps of Engineers, 1991).

The input files to the HEC-6 model are alphanumerically coded records grouped according to data content, geometry, sediment, hydrology, and special commands. Geometric data are in the format of the HEC-2 step-backwater program (U.S. Army Corps of Engineers, 1984). Water-surface profiles are computed with the standard step method of that program. For each cross section, special records define bed thickness, limits of the movable and fixed parts of the bed, and the limits of dredging, as an option.

Data on the sediment content of inflows consist of particle-size fractions of mean daily loads associated with as many as nine discharge values, which are selected to define the full range of the sediment-transport curve. Bedload fractions, if significant, are included with these suspended-sediment data. Particle-size fractions of bed deposits in the reservoirs are coded for each of the cross sections.

User-specified variables for sediment-transport computations include a choice of 10 sediment-transport functions for sand or, alternatively, user-determined transport coefficients; choices for fall-velocity and bed-shear computation methods; specific gravities for clay, silt, and sand; shear-stress thresholds for both deposition and erosion of clay and silt; shear-stress thresholds for mass erosion of clay and silt; mass-erosion rate; unit weights of unconsolidated and consolidated bed deposits; compaction coefficients; and a grain-shape factor for sand.

In the hydrologic-data records, the outflow discharge at the downstream end of the reservoir and as many as nine local inflow and outflow discharges for tributaries and diversions in the modeled reach are coded as a single record. Another record indicates the durations, in days, for each of these discharges. Temperatures of the inflows are a required input. Sets of discharge, duration, and temperature records are sequenced to hydrographically describe the simulation period.

Application of Model to Reservoir System

Development

The HEC-6 model for the Clarke-Aldred-Conowingo Reservoir system was prepared from the previously described seismic data on water depths and sediment thickness and from the particle-size fractions of accumulated and inflow sediments. Representative cross-sectional data were developed at selected intervals from the centerline of Conowingo Dam to the streamflow gage on the Susquehanna River at Marietta, Pa.

Hydraulic calibration of the model generally followed the procedures in the HEC-6 model calibration and application document (U.S. Army Corps of Engineers, 1981). Manning's roughness coefficients were chosen on the basis of field observations and values previously used in modeling similar channels. Starting water-surface elevations at Conowingo Dam were determined with a rating curve, which was developed from the dam-tender's forebay water-surface elevations and corresponding discharges at the USGS streamflow gage at the tailrace. Because the HEC-6 model will accept only one rating curve for a stream subarea, previous measurements of forebay elevations and discharges for the Holtwood and Safe Harbor Dams were used to develop simple dam-geometry models that approximated the discharges through and over both hydroelectric dams. The developed hydraulic model closely replicated the high-water profile of the 1972 flood, as documented by Miller (1974), in the reach from Conowingo Dam to Marietta, Pa.

Simulation of sediment transport with the HEC-6 model was calibrated by attempting to reproduce monthly and annual inflows and outflows of sediment loads for calendar year 1987. These loads were computed with version 90.10 of a program by Cohn and others (1989). The sediment-transport relations for calculating inflow loads were developed from 125 measurements of suspended-sediment concentrations and corresponding instantaneous water discharges that were made from 1987-89 at the streamflow gage on the Susquehanna River at Marietta, Pa. (USGS number 01576000), and from 410 similar measurements made during that same period at the streamflow gage on the Conestoga River at Conestoga, Pa. (USGS number 01576754). To include the drainage area and loads of the adjacent Pequea Creek Basin, which has similar sediment yields, loads computed for the Conestoga River at Conestoga were multiplied by 1.34, a factor that is based on the size of the Pequea Creek Basin. The effective drainage area represented by the computed sediment inflows of the Susquehanna River, Conestoga River, and Pequea Creek is about 26,620 mi^2, or 98.2 percent of the drainage area at Conowingo Dam.

For consistency, the Cohn program was used to compute monthly and annual loads of sediment discharged from the reservoir system. A data set that contained 215 pairs of sediment-concentration and discharge measurements made at the streamflow gage on the Susquehanna River at Conowingo during 1987-89 was used to calculate the loads. For 1987, the sediment load calculated by the Cohn model for the Susquehanna River at Conowingo was 565,000 tons. This load compares closely with the load of 539,000 tons calculated by directly integrating sediment concentrations and water discharge.

Initial estimates of the mean fractions of 13 standard particle sizes, from clay to medium gravel, associated with various flows at Marietta and discharges from the Conestoga River and Pequea Creek, were developed from a manually prepared sediment-transport curve and available particle-size analyses of suspended sediment.

The sediment-transport curve for Marietta was developed from a selected set of sediment-concentration data collected at the Marietta gage (107 of 125 calculations) during 1987-89, and 15 load calculations made for the flood of June 1972 at the gage on the Susquehanna River at Harrisburg, Pa., about 25 mi upstream of Marietta. The curve was given a positive bias of 4 percent—2 percent to allow for 480 mi^2 of ungaged area and 2 percent, as an estimate, for unmeasured bedload.

Because no particle-size determinations of suspended sediment were available at the Marietta gage, 9 particle-size analyses samples collected from the Susquehanna River at Harrisburg, Pa., in 1980, 1981, and 1989 were used to estimate transport curves for 10 size fractions (1 clay, 4 silt, and 5 sand sizes) at Marietta. Throughout the observed range of water discharge, clay loads were reduced by 50 percent to convert the loads, as determined by standard laboratory analysis, to "natural" loads. Loads of very fine silt were increased by the same amounts that clay loads were reduced. This conversion was based on comparison of a mechanically and chemically dispersed particle-size distribution with a mechanically dispersed particle-size distribution collected from Bixler Run, a stream located near the center of the Lower Susquehanna River Basin, during a wintertime flood in 1965. Laboratory particle-size analysis results in a misrepresentation of the actual sizes of particles suspended in the streamflow caused by the physical and chemical breakdown of colloids during the analyses (Guy, 1969). Better model results would probably be obtained if in situ (undispersed) particle-size data were available. The initial HEC-6 input of fractional distributions of particle sizes in the total sediment load at Marietta and from ungaged areas, representing the contribution from 26,470 mi^2, are listed in table 6 for selected discharges.

Table 6. *Initial estimates of fractional distributions of particle loads for selected discharges of the Susquehanna River at Marietta, Pa.*

Particle size	Discharge, in cubic feet per second							
	1,000	10,000	35,000	50,000	100,000	200,000	500,000	1,000,000
Natural clay	0.34	0.28	0.26	0.25	0.23	0.22	0.19	0.18
Very fine silt	.45	.40	.38	.36	.33	.30	.27	.25
Fine silt	.08	.10	.105	.11	.12	.12	.13	.14
Medium silt	.06	.08	.085	.09	.10	.11	.12	.13
Coarse silt	.02	.04	.055	.06	.07	.07	.075	.08
Very fine sand	.04	.04	.045	.05	.05	.055	.055	.05
Fine sand	.01	.03	.035	.04	.04	.045	.045	.04
Medium sand	0	.01	.01	.01	.02	.02	.03	.035
Coarse sand	0	.01	.01	.01	.01	.015	.02	.025
Very coarse sand	0	.01	.01	.01	.01	.015	.02	.02
Very fine gravel	0	0	.005	.01	.01	.015	.02	.02
Fine gravel	0	0	0	0	.01	.01	.015	.02
Medium gravel	0	0	0	0	0	.005	.01	.01

The sediment-transport curve for the Conestoga River and Pequea Creek Basins was developed from the concentrations of 108 suspended-sediment samples collected during 1985-89 at the Conestoga River gage. The transport curve was partitioned into particle-size curves on the basis of 11 particle-size analyses of suspended sediment collected at the gage from 1987 through 1989. As with the Susquehanna River at Marietta curves, half of the "laboratory" clay loads were shifted to the very-fine-silt fraction in approximating the "natural" size distributions of loads. The initial input of fractional particle-size distributions for the Conestoga River and Pequea Creek, representing 630 mi^2, are listed in table 7.

Table 7. *Initial estimates of fractional distributions of particle loads for selected discharges of the Conestoga River and Pequea Creek Basins*

Particle size	Discharge, in cubic feet per second							
	80	100	1,000	2,000	5,000	10,000	30,000	90,000
Natural clay	0.40	0.36	0.30	0.29	0.27	0.25	0.22	0.20
Very fine silt	.56	.54	.47	.45	.40	.38	.34	.30
Fine silt	.03	.06	.11	.12	.14	.15	.165	.17
Medium silt	.005	.02	.06	.065	.086	.095	.105	.12
Coarse silt	.005	.01	.03	.037	.053	.060	.070	.080
Very fine sand	0	.01	.015	.018	.023	.025	.037	.048
Fine sand	0	0	.01	.013	.015	.020	.033	.042
Medium sand	0	0	.005	.007	.01	.01	.017	.020
Coarse sand	0	0	0	0	.003	.01	.013	.015
Very coarse sand	0	0	0	0	0	0	0	.005
Very fine gravel	0	0	0	0	0	0	0	0
Fine gravel	0	0	0	0	0	0	0	0
Medium gravel	0	0	0	0	0	0	0	0

Bed composition throughout the three reservoirs was determined from particle-size analyses of bed materials. The clay and very-fine-silt fractions were adjusted to "natural" size fractions in the same manner as were the suspended-sediment loads. Fractional particle-size distributions at the selected cross sections were determined from an interpolation of particle-size fraction profiles along each reservoir. The bed sections below each dam and at cross sections in the swift-water parts of the study reach were assumed, for coding purposes, to have a thin layer (usually 0.01 ft) of silt.

Calibration

The HEC-6 model was calibrated on the basis of observed inflows for calendar year 1987. The goal was to approximate the trap efficiency of the reservoir system calculated by the difference between the reference inflow and outflow loads determined with the Cohn model. No load observations are available for evaluating how well the transport and deposition of sediment was simulated within individual reservoirs or between reservoirs. Also, no particle-size data are available to evaluate the simulation of clay, silt, and sand loads discharged at Conowingo Dam.

Step-wise hydrographic data were used to partition inflow to the reservoirs for calendar year 1987. Thirty-four time steps were used to code the 1987 hydrograph. Water-discharge values for the Conestoga River-Pequea Creek contributions were determined from the equation

$$Q_c = \log (Q5765 + 0.5) / 1.05, \qquad (7)$$

where Qc is total discharge of Conestoga River and Pequea Creek Basins, and
Q5765 is mean discharge at the Conestoga River at Lancaster, Pa., a long-term streamflow-gaging station (USGS number 01576500).

Data from the long-term streamflow-gaging station at Lancaster were used instead of multiplying discharge for Conestoga River at Conestoga by 1.34 to include discharge from Pequea Creek. The greater length of water-discharge record at the Lancaster streamflow-gaging station should increase the accuracy of the estimate of water discharge for the Conestoga and Pequea Creek Basins.

Water-temperature data were derived from annual trend curves for stream temperatures at the Harrisburg and Lancaster gages (Flippo, 1975). Temperatures were specified at a sufficient number of intervals to describe the seasonal trend of water temperatures.

Sediment properties and transport parameters were selected in accordance with guidelines provided by the HEC-6 User's Manual (U.S. Army Corps of Engineers, 1991). Initially, the specific gravities for clay and silt were those determined by analysis of bed deposits. However, a final value of 2.65 was selected because of the high transport rate initially calculated for these fractions. A value of 2.1 for sand was determined by proportional weighting of the specific gravities of the coal and sand fractions. Depositional shear-stress thresholds of 0.022 and 0.024 lb/ft^2 were estimated for the surficial and deeper bed layers, respectively. Provision was made for 140 iterations of the Exner equation. Even with this many iterations, it was sometimes necessary to code short time steps for low to moderate inflows in order to avoid math errors in the computations.

Model computations for the calibration year of 1987 resulted in low trap efficiencies, even though the computational options that gave the highest trap efficiencies were selected. For the year, the initial HEC-6 model run resulted in a trap efficiency of 33.8 percent, as compared to the reference efficiency of 71.0 percent from the Cohn model. Differences between the HEC-6 model results and the reference trap efficiencies for both high- and low-flow periods were similar.

Inspection of the HEC-6 model simulation transport summaries indicated that no sand and only small amounts of coarse silt passed through the reservoirs during 1987. This result was reasonable because the peak water discharge during the year was 236,000 ft^3/s. Model simulations indicated that much of the finer silt and virtually all the clay would pass through the reservoir system. The resulting sediment load calculated as leaving the reservoir system in 1987 was significantly more than the load simulated in the Cohn model, as well as the load computed by integrating the concentration and flow data. The option selected to obtain realistic trap efficiencies was a further shifting of the particle-size distributions listed on table 6 so that less clay and more silt and sand would enter the system. Consequently, transport curves for the various fractions of the inflow sediment were adjusted to provide for coarser-grained loads. Total tonnage/discharge relations were not changed. The adjustment to the initial curves was made by successive trial steps until the computed trap efficiency for the reservoir system was within one standard error of the Cohn efficiency value. The original and revised fractional distributions of particle loads for the Marietta inflow and the Conestoga River-Pequea Creek inflows are given, respectively, in tables 8 and 9.

Table 8. *Original and revised fractional distributions of particle loads for selected discharges of the Susquehanna River at Marietta, Pa.*

[O, original value; R, revised value]

Particle size	Discharge, in cubic feet per second															
	1,000		10,000		35,000		50,000		100,000		200,000		500,000		1,000,000	
	O	R	O	R	O	R	O	R	O	R	O	R	O	R	O	R
Natural clay	0.34	0.200	0.28	0.166	0.26	0.148	0.25	0.142	0.23	0.132	0.22	0.120	0.19	0.104	0.18	0.090
Very fine silt	.45	.180	.40	.156	.38	.143	.36	.138	.33	.129	.30	.118	.27	.103	.25	.089
Fine silt	.08	.190	.10	.165	.105	.151	.11	.147	.12	.137	.12	.126	.13	.111	.14	.096
Medium silt	.06	.197	.08	.174	.085	.156	.09	.150	.10	.140	.11	.130	.12	.115	.13	.103
Coarse silt	.02	.182	.04	.160	.055	.136	.06	.134	.07	.124	.07	.117	.075	.107	.08	.104
Very fine sand	.04	.049	.04	.065	.045	.076	.05	.079	.05	.086	.055	.094	.055	.105	.05	.115
Fine sand	.01	.002	.03	.057	.035	.082	.04	.088	.04	.097	.045	.105	.045	.114	.04	.120
Medium sand	0	0	.01	.036	.01	.062	.01	.068	.02	.082	.02	.093	.03	.103	.035	.110
Coarse sand	0	0	.01	.017	.01	.035	.01	.040	.01	.052	.015	.064	.02	.077	.025	.085
Very coarse sand	0	0	.01	.004	.01	.011	.01	.014	.01	.020	.015	.029	.02	.047	.02	.054
Very fine gravel	0	0	0	0	.005	0	.01	0	.01	.001	.015	.003	.02	.011	.02	.020
Fine gravel	0	0	0	0	0	0	0	0	.01	0	.01	.001	.015	.002	.02	.009
Medium gravel	0	0	0	0	0	0	0	0	0	0	.005	0	.01	.001	.01	.005

Table 9. *Original and revised fractional distributions of particle loads for selected discharges of the Conestoga River and Pequea Creek Basins*

[O, original value; R, revised value]

Particle size	Discharge, in cubic feet per second															
	80		100		1,000		2,000		5,000		10,000		30,000		90,000	
	O	R	O	R	O	R	O	R	O	R	O	R	O	R	O	R
Natural clay	0.40	0.320	0.36	0.310	0.30	0.240	0.29	0.220	0.27	0.200	0.25	0.190	0.22	0.170	0.20	0.150
Very fine silt	.56	.200	.54	.195	.47	.150	.45	.140	.40	.131	.38	.125	.34	.118	.30	.110
Fine silt	.03	.190	.06	.185	.11	.143	.12	.135	.14	.128	.15	.122	.165	.117	.17	.107
Medium silt	.005	.180	.02	.175	.06	.136	.065	.131	.086	.126	.095	.122	.105	.119	.12	.118
Coarse silt	.005	.110	.01	.115	.03	.130	.037	.134	.053	.134	.060	.134	.070	.134	.080	.135
Very fine sand	0	0	.01	.020	.015	.098	.018	.110	.023	.123	.025	.133	.037	.144	.048	.155
Fine sand	0	0	0	0	.01	.075	.013	.091	.015	.106	.020	.117	.033	.133	.042	.150
Medium sand	0	0	0	0	.005	.028	.007	.037	.01	.049	.01	.053	.017	.060	.020	.067
Coarse sand	0	0	0	0	0	0	0	.002	.003	.003	.01	.004	.013	.005	.015	.007
Very coarse sand	0	0	0	0	0	0	0	0	0	0	0	0	0	0	.005	.001
Very fine gravel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fine gravel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Medium gravel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Results

A summary of the calibration results is listed in tables 10 and 11. An example of a detailed output summary, the cumulative bed change, as well as the water-surface elevation, thalweg elevation, the modeled discharge, and sediment loads, by size fraction for each cross section, for the December 30-31 time step is listed in table 10. The sediment load listed is the amount passing each section, in tons per day. A summary of the fractional sediment loads in acre-feet passed between the reservoirs during the calibration run is listed in table 11. Also included are the trap efficiencies of each reservoir for the total sediment load. The input at river mile 32.110 reflects the tributary inflow of the Conestoga River and Pequea Creek.

These data indicate that about 33 percent of the clay, 61 percent of the silt, and 100 percent of the sand in the inflow sediment loads during 1987—a typical year—were trapped by the reservoirs. Thirty-five percent of the inflow sediment as computed in the HEC-6 model simulation, or 563,000 tons, passed through Conowingo Dam.

Summaries of annual loads and trap efficiencies obtained after the revision to the model input parameters for the calibration year of 1987 and the verification years of 1988 and 1989 are given for the HEC-6 model in table 12. Loads computed in the Cohn model and by a hand-integration technique also are presented in table 12. Mean inflows for each of the 117 time steps used to input the 3 years of hydrographic data into the model agreed within 10 percent with the corresponding mean water discharges at the streamflow-gaging station on the Susquehanna River at Conowingo, Md. (USGS number 01578310). Annual inflow and outflow water discharges agreed within 3 percent.

High-flow sediment transport was not simulated in the HEC-6 model as well as the data of table 12 indicates. The results of simulated sediment transport for May and June 1972 are summarized in table 13. The peak flood of record occurred during this period. The simulation indicated that clay and silt were scoured from the reservoirs in amounts equal to about half of the load measured during the 2-month period. Additionally, the simulation indicated that 86 percent of the sand in the inflow was trapped. These results are inconsistent with data collected from the Susquehanna River at Harrisburg, Pa., and at Conowingo, Md., during the flood of June 1972. From June 21 through June 30, 1972, the measured sediment load transported by the Susquehanna River at Harrisburg was 7.52 million tons, and the load transported by the Susquehanna River at Conowingo was 34.8 million tons. Sediment scoured from the three reservoirs may have been more than 23 million tons instead of the 2 million tons of deposition simulated in the model.

Table 10. *Summary output from the HEC-6 model showing bed-surface and water-surface elevation change, the simulated discharge, and the sediment load passing each cross section in the Lower Susquehanna River reservoir system, December 30-31, 1987*

Section number	Bed-surface elevation change (feet)	Water-surface elevation (feet)	Thalweg elevation (feet)	Water discharge (cubic feet per second)	Fractional sediment load (tons per day)		
					Clay	Silt	Sand
44.900	-0.01	238.29	229.49	34,000	359	1,421	660
44.400	-.01	237.95	228.99	34,000	359	1,421	667
43.580	-.01	234.12	230.49	34,000	359	1,421	667
43.000	-.05	226.93	220.95	34,000	359	1,421	675
41.230	-.08	226.03	217.92	34,000	359	1,421	161
39.240	.43	226.02	208.43	34,000	319	795	0
37.810	.08	226.02	206.08	34,000	294	627	0
37.000	.07	226.01	193.07	34,000	278	552	0
35.750	.05	226.01	193.05	34,000	260	480	0
33.810	.03	226.01	194.03	34,000	246	435	0
32.840	.02	226.00	193.02	34,000	238	412	0
32.382	-.01	226.00	192.99	34,000	237	410	0
32.381	.06	226.00	175.06	34,000	237	410	0
32.380	-.01	192.80	174.99	34,000	237	410	0
32.300	.00	169.18	155.00	34,000	237	410	0
32.110	-.04	168.41	157.96	34,550	244	426	33
31.010	.00	168.30	152.00	34,550	241	418	23
29.530	.17	168.29	137.17	34,550	232	394	0
28.670	.04	168.28	139.04	34,550	226	378	0
27.330	.04	168.27	146.04	34,550	220	362	0
26.440	.04	168.27	126.04	34,550	217	354	0
25.970	.01	168.26	93.01	34,550	214	347	0
24.960	-.02	168.26	124.98	34,550	214	347	1
24.691	.00	167.50	150.00	34,550	214	347	0
24.690	-.01	159.44	149.99	34,550	214	347	0
24.650	.00	109.72	104.00	34,550	214	347	0
24.270	.00	108.14	70.00	34,550	214	347	0
23.170	.00	107.41	75.00	34,550	214	347	0
22.500	-.06	107.21	81.94	34,550	214	347	0
21.230	.01	107.14	93.01	34,550	208	335	0
20.010	.05	107.13	89.05	34,550	190	291	0
18.400	.04	107.12	84.04	34,550	173	254	0
17.260	.03	107.11	81.53	34,550	160	228	0
16.000	.04	107.11	65.04	34,550	148	205	0
14.800	.04	107.11	65.04	34,550	138	187	0
13.840	.03	107.11	74.03	34,550	128	170	0
12.520	.03	107.11	54.03	34,550	121	159	0
11.530	.02	107.11	56.52	34,550	116	150	0
10.320	.01	107.11	42.01	34,550	113	145	0
9.743	.01	107.11	42.01	34,550	112	144	0
9.742	.00	107.11	42.00	34,550	112	144	0
9.740	.01	107.11	90.01	34,550	112	144	0

Table 11. *Summary output from HEC-6 model calibration run showing 1987 sediment load introduced to each reservoir on the Susquehanna River and sediment load trap efficiency*

[--, not applicable]

Reservoir	Entry / Exit River Mile	Clay In (acre-feet)	Clay Out (acre-feet)	Clay Trap efficiency (percent)	Silt In (acre-feet)	Silt Out (acre-feet)	Silt Trap efficiency (percent)	Sand In (acre-feet)	Sand Out (acre-feet)	Sand Trap efficiency (percent)
Clarke	44.900	325.15	–	–	705.68	–	–	382.78	–	–
	32.381	[1] (325.15)	282.50	13	(705.68)	423.25	40	(382.78)	0.58	100
Aldred	32.381	282.50	–	–	423.25	–	–	.58	–	–
	32.110	58.52	–	–	82.62	–	–	39.62	–	–
	24.691	(341.02)	327.99	4	(505.87)	463.39	8	(40.20)	14.27	65
Conowingo	24.691	327.99	–	–	463.39	–	–	14.27	–	–
	9.74	(327.99)	257.55	21	(463.39)	305.33	34	(14.27)	.00	100

[1] Numbers in parentheses are the total measured inputs to the reservoir.

Table 12. *Loads and trap efficiencies for the three-reservoir system on the Lower Susquehanna River, as computed in the HEC-6 and Cohn models, and by a hand-integration method*

[--, not applicable]

Year	Flow type	HEC-6 model: Load, in thousands of tons: Clay	Silt	Sand	Total	HEC-6 model: Trap efficiency (percent)	Cohn model: Total load (thousands of tons)	Cohn model: Trap efficiency (percent)	Integration method: Total load (thousands of tons)	Integration method: Trap efficiency (percent)
1987	Inflow	384	788	368	1,594	–	1,945	–	—	–
	Outflow	258	305	0	563	64.7	565	71.0	539	72.3
1988	Inflow	253	930	557	1,740	–	1,850	–	—	–
	Outflow	165	358	0	523	69.9	428	76.9	450	75.7
1989	Inflow	516	1,982	1,308	3,806	–	3,730	–	—	–
	Outflow	400	901	0	1,301	65.8	990	73.4	917	75.4

Table 13. *HEC-6 loads and trap efficiencies for the three-reservoir system on the Lower Susquehanna River, May and June 1972*

	Load (thousands of tons): Clay	Silt	Sand	Total
Inflow				
Marietta	1,122	4,791	5,560	11,473
Conestoga-Pequea	211	637	484	1,332
Total inflow	1,333	5,428	6,044	12,805
Outflow				
Conowingo Dam	2,003	7,903	860	10,766
Trap efficiency (percent):	-50	-46	86	16

SUMMARY AND CONCLUSIONS

The Susquehanna River drains 27,510 mi^2 in New York, Pennsylvania, and Maryland and is the largest tributary to the Chesapeake Bay. Three large hydroelectric dams span the Susquehanna River. Safe Harbor (Lake Clarke) and Holtwood (Lake Aldred) are in southern Pennsylvania, and Conowingo (Conowingo Reservoir) is in northern Maryland, about 10 mi upstream of the Chesapeake Bay. The reservoirs behind the dams have trapped large quantities of sediment, nitrogen, and phosphorus.

In the fall of 1990, sediment deposition in the three reservoirs amounted to about 259 million tons; Conowingo Reservoir, about 155 million tons; Lake Clarke, about 90.7 million tons; and Lake Aldred, about 13.6 million tons. The sediment from all three reservoirs was composed of 64.8 million tons of sand, 19.7 million tons of coal, 112 million tons of silt, and 63.3 million tons of clay. About 33 percent of the sediment in the three reservoirs was sand and coal. The percentage of sand and coal ranged from 75 percent in the upper part of Conowingo Reservoir to 7 percent in the lower part of Conowingo Reservoir. Sediment in the lower part of Conowingo Reservoir averaged 58 percent silt, 35 percent clay, 2 percent coal, and 5 percent sand. The sediment in the reservoirs contained about 814,000 tons of organic nitrogen, 98,900 tons of ammonia as nitrogen, 226,000 tons of phosphorus, 5,610,000 tons of iron, 2,250,000 tons of aluminum, and about 409,000 tons of manganese. Deposition in the reservoirs was variable and ranged from areas of little or no deposition to depths of about 30 ft.

Lake Aldred and Lake Clarke reached equilibrium with incoming river sediment by 1910 and 1950, respectively, and are no longer storing sediment. The original capacity (in 1928) of the reservoir formed by Conowingo Dam was about 300,000 acre-ft. By 1959, deposition of sediment reduced the capacity to 235,000 acre-ft, and by 1990, the capacity was only 196,000 acre-ft. A comparison of the cross-sectional data from Lake Aldred and Lake Clarke with those of Conowingo Reservoir indicates that the Conowingo Reservoir will probably reach equilibrium in the next 20 or 30 years. As the reservoirs fill, the percentage of sediment, nitrogen, phosphorus, and metals transported by the Susquehanna River that is deposited in the reservoirs will decrease, and the percentage that reaches Chesapeake Bay will increase. Historical inflow and outflow data indicate that the reservoirs scour when the flow of the Susquehanna River at Conowingo, Md., exceeds 400,000 ft^3/s.

The U.S. Army Corps of Engineers' HEC-6 sediment-transport model was used to simulate sediment-transport dynamics. Although the model selected was determined to be the most suitable model available to this study, simulated trap efficiencies were lower than measured values. During the year when the model was calibrated, the measured trap efficiency of the reservoir system was about 76 percent. The maximum efficiency that could be reproduced by the model using 'natural' particle-size distribution was about 34 percent. Measured trap efficiencies were reproduced only after the particle-size distribution of the inflow was shifted to a more coarse grained sediment.

Additional channel geometry and sediment-transport data may slightly improve the results of this model. The major limitation of the model appears to be the algorithms used to transport the various particle-size fractions. A review and redefinition of these algorithms are required to significantly improve the results of this model and the understanding of the sediment-transport dynamics of the Lower Susquehanna River reservoir system.

REFERENCES CITED

Clark, L.J., Donnelly, D.K., and Villa, Orterio, 1973, Nutrient enrichment and control requirements in the upper Chesapeake Bay: U.S. Environmental Protection Agency, Region III, Annapolis field office, Technical Report 56, 58 p.

Clark, L.J., Guide, Victor, and Phieffer, T.H., 1974, Summary and conclusions, Nutrient transport and accountability in the lower Susquehanna River Basin: U.S. Environmental Protection Agency, Region III, Annapolis field office, Technical Report 60, 91 p.

Cohn, T.A., DeLong, L.L., Gilroy, E.J., Hirsch, R.M., and Wells, D.K., 1989, Estimating constituent loads: Water Resources Research, v. 25, no. 5, p. 937-942.

Cooper, H.M., Snyder, N.H., Abernethy, R.F., Tarpley, R.C., and Swingle, R.J., 1944, Analyses of mine, breaker, and delivered samples, p. 40-173, *in* Analysis of Pennsylvania anthracitic coals: U.S. Department of the Interior, Bureau of Mines, 271 p.

Durlin, R.R., and Schaffstall, W.P., 1992, Water resources data, Pennsylvania, water year 1991: U.S. Geological Survey Water-Data Report PA-91-2, 322 p.

Fan, Shou-Shan, ed., 1988, Twelve selected computer stream sedimentation models developed in the United States: Washington, D.C., Federal Energy Regulatory Commission, 552 p.

Fishel, D.K., 1984, Water-quality and chemical loads of the Susquehanna River at Harrisburg, Pennsylvania, April 1980 to March 1981: U.S. Geological Survey Water-Resources Investigations Report 83-4164, 90 p.

Flippo, H.N., Jr., 1975, Temperatures of streams and selected reservoirs in Pennsylvania: Pennsylvania Department of Environmental Resources, Water Resources Bulletin 11, 95 p.

Gorin, S.R., and Haeni, F.P., 1988, Use of surface-geophysical methods to assess riverbed scour at bridge piers: U.S. Geological Survey Water-Resources Investigations Report 88-4212, 83 p.

Gross, M.G., Karweit, M., Cronin, W.B., and Schubel, J.R., 1978, Suspended sediment discharge of the Susquehanna River to northern Chesapeake Bay, 1966-1976: Estuaries, v. 1, p. 106-110.

Guy, H.P., 1969, Laboratory theory and methods for sediment analysis: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. C1, 58 p.

James, R.W., Jr., Simmons, R.H., and Strain, B.F., 1988, Water resources data, Maryland and Delaware, water year 1987: U.S. Geological Survey Water-Data Report MD-DE-87-1, 470 p.

James, R.W., Jr., Simmons, R.H., Strain, B.F., and Smigaj, M.J., 1989, Water resources data, Maryland and Delaware, water year 1988: U.S. Geological Survey Water-Data Report MD-DE-88-1, 590 p.

Lang, D.J., 1982, Water quality of the three major tributaries to the Chesapeake Bay, The Susquehanna, Potomac, and James Rivers, January 1979-April 1981: U.S. Geological Survey Water-Resources Investigations Report 82-32, 64 p.

Ledvina, J.P., 1962, 1961 Holtwood River bed silt survey, Holtwood Dam to Shenk's Ferry, September-November 1961: Holtwood Steam Electric Station and the Pennsylvania Power and Light Company, Holtwood, Pa., 80 p.

Levin, Paul, and Smith, D.I., 1954, A modern river coal recovery operation on the Susquehanna River: Atlantic City Convention, American Society of Civil Engineers, June 15-18, 1954, 35 p.

Lietman, P.L., Ward, J.R., and Behrendt, T.E., 1983, Effects of specific land uses in nonpoint sources of suspended sediment, nutrients, and herbicides-Pequea Creek Basin, Pennsylvania, 1979-80: U.S. Geological Survey Water-Resources Investigations Report 83-4113, 88 p.

Lloyd, O.B., Jr., and Growitz, D.J., 1977, Ground-water resources of central and southern York County, Pennsylvania, Pennsylvania Geological Survey, 4th ser., Water Resources Report 42, 93 p.

Loper, W.C., and Behrendt, T.E., and Schaffstall, W.P., 1988, Water resources data, Pennsylvania, water 1987: U.S. Geological Survey Water-Data Report PA-87-2, 322 p.

_____1989, Water resources data, Pennsylvania, water 1988: U.S. Geological Survey Water-Data Report PA-88-2, 276 p.

McLean, R.I., Summers, J.K., Olsen, C.R., Domotor, S.L., Larsen, I.L., and Wilson, H., 1991, Sediment accumulation rates in Conowingo Reservoir as determined by man-made and natural radionuclides: Estuaries, v. 14, no. 2, p. 148-156.

Miller, C.R., 1951, Analysis of flow-duration, sediment-rating curve method of computing sediment yield: U.S. Bureau of Reclamation, Hydrology Branch, Project Planning Division, Denver Colo., 55 p.

Miller, R.A., 1974, Hydrologic data of the June 1972 flood in Pennsylvania: Pennsylvania Department Environmental Resources, Water Resources Bulletin 9, 97 p.

Officer, C.B., Lynch, D.R., Setlock, G.H., and Helz, G.R., 1984, Recent sedimentation rates in Chesapeake Bay *in* Kennedy, V., ed., The estuary as a filter: New York, Academic Press, p. 131-157.

Ott, A.N., Takita, C.S., Edwards, R.E., and Bollinger, S.W., 1991, Loads and yields of nutrients and suspended sediment transported in the Susquehanna River Basin, 1985-89: Susquehanna River Basin Report, Pub. No. 136, 253 p.

Philadelphia Electric Company, 1989, Recreation areas on Conowingo Pond, Map, 2 p.

Porterfield, George, 1972, Computation of fluvial-sediment discharge: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. C3, 66 p.

Poth, C.W., 1977, Summary of ground-water resources of Lancaster County, Pennsylvania: Pennsylvania Geological Survey, 4th ser., Water Resources Report 43, 80 p.

Schuleen, E.T., and Higgins, G.R., 1953, Analysis of suspended-sediment measurements for Lake Clarke, inflow and outflow, 1948-53: Pennsylvania Power and Light Co. Report no. 970, p. 1-40.

Sisler, J.D., Fraser, Thomas, and Ashmead, D.C., 1928, Anthracite culm and silt: Pennsylvania Topographic and Geological Survey, 4th ser., Mineral Resource Report 12, 268 p.

Susquehanna River Basin Study Coordinating Committee, 1970, Susquehanna River Basin Study, Appendix H - Power: 41 p.

Taylor, L.E., and Werkheiser, W.H., 1984, Ground-water resources of the Lower Susquehanna River Basin, Pennsylvania: Pennsylvania Geological Survey, 4th ser., Water Resources Report 57, 100 p.

U.S. Army Corps of Engineers, 1981, Guidelines for the calibration and application of computer program HEC-6: Davis, Calif., Hydrologic Engineering Center training document no. 13, 38 p.

_____1984, HEC-2 Water surface profiles --User's manual: Davis, Calif., The Hydrologic Engineering Center, [variously paged].

_____1987, COED - Corps of Engineers Editor: Davis, Calif., The Hydrologic Engineering Center, [variously paged].

_____1991, HEC-6 Scour and deposition in rivers and reservoirs --User's manual: Davis, CA, Hydrologic Engineering Center report CPD-6 [variously paged].

U.S. Department of Commerce, 1990, Climatological Data for Pennsylvania, Volume 95-13: National Oceanic and Atmospheric Administration, Environmental Data Service.

Ward, J.R., and Eckhardt, D.A., 1979, Nonpoint-source discharges in Pequea Creek Basin, Pennsylvania, 1977: U.S. Geological Survey Water-Resources Investigations 79-88, 110 p.

Ward, J.R., 1987, Surface-water quality in Pequea Creek Basin, Pennsylvania, 1977-79: U.S. Geological Survey Water-Resources Investigations Report 85-4250, 66 p.

Whaley, R.C., 1960, Physical and chemical limnology of Conowingo Reservoir: The Chesapeake Bay Institute, Johns Hopkins University, Technical Data Report 32, 140 p.

Williams, K.F., and Reed, L.A., 1972, Appraisal of stream sedimentation in the Susquehanna River Basin: U.S. Geological Survey Water-Supply Paper 1532-F, 24 p.

Wolansky, R.M., Haeni, F.P., and Sylvester, R.B., 1982, Continuous seismic-reflection survey defining shallow sedimentary layers in the Charlotte Harbor and Venice areas, southwest Florida: U.S. Geological Survey Water-Resources Investigations Report 82-57, 83 p.

APPENDIX B

ISSUES REGARDING ESTIMATED IMPACTS OF THE LOWER SUSQUEHANNA RIVER RESERVOIR SYSTEM ON SEDIMENT AND NUTRIENT DISCHARGE TO THE CHESAPEAKE BAY

THE ACADEMY OF NATURAL SCIENCES OF PHILADELPHIA
Report No. 94-20

Issues Regarding Estimated Impacts of the Lower Susquehanna River Reservoir System on Sediment and Nutrient Discharge to Chesapeake Bay

Report No. 94–20

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Introduction

The 1987 Chesapeake Bay Agreement requires that controllable nutrient loads to Chesapeake Bay be reduced by 40%, compared to 1985 levels. Nutrients are transported to the Bay primarily by its many tributaries. They are important because they increase the magnitude of phytoplankton blooms, leading to decreased dissolved oxygen levels as the resulting organic debris decomposes. Suspended sediments carried by the tributaries are also of concern because of the particle-bound nutrients they carry, and because they reduce light transmitted to submerged aquatic vegetation and degrade living conditions for benthic stages of aquatic organisms such as oysters and striped bass (e.g., Sherk 1972).

The Susquehanna River is the only tributary that discharges directly into the Bay rather than an intervening estuary. During periods without major storms, estuaries like those on the James and Potomac rivers act as efficient sediment traps, retaining 95 to 100% of influent sediment (Officer and Nichols, 1980; Biggs and Howell, 1984). The Susquehanna lacks such an estuary but possesses a different type of sediment trap: a sequence of three closely-spaced reservoirs downstream from Columbia, Pennsylvania (Fig. 1). Cumulatively, these three reservoirs are estimated to contain roughly 212 million tons of sediment (Hainly et al., draft), with estimates of overall trapping efficiency ranging from 40 to 78% for periods without major storms (see below).

Two of the lower Susquehanna reservoirs are thought to be near steady state with regard to total bed-sediment (Lake Clarke and Lake Aldred), while net deposition is thought still to be occurring in the third (Conowingo Reservoir). As the sediment content of Conowingo Reservoir increases and approaches its steady-state level, net deposition will decrease and sediment throughput will increase. Two concerns have arisen regarding these anticipated trends. First, how will the increased throughput of sediment and particle-bound nutrients affect Chesapeake Bay? And second, how will the increased sediment content of the reservoir system alter the impact of a major flood on the Bay?

In an effort to supply partial answers to these questions, the USGS conducted a study of sediment, nutrients, and metals transported through the lower Susquehanna River (Hainly et al., draft). The study included empirical estimates of input to and output from the reservoir system, and also included implementation of a one-dimensional sediment transport model for studying the time-course of reservoir filling and the scouring effects of floods. The final version of the USGS report has not yet appeared, but a preliminary draft has been circulated for comment.

The purpose of the present report is to highlight several unresolved issues in the USGS draft report which we believe have a bearing on the usefulness of the results. These issues concern the role of the three lower Susquehanna reservoirs in altering sediment and nutrient discharge to Chesapeake Bay.

The Lower Susquehanna Reservoir System

Three hydroelectric dams are situated on the lower Susquehanna River between Columbia, Pennsylvania and Chesapeake Bay (Fig 1). In upstream to downstream order, these are the Safe Harbor, Holtwood, and Conowingo dams. The corresponding

impoundments are Lake Clarke, Lake Aldred, and Conowingo Reservoir. Holtwood Dam was completed in 1910 and is the oldest of the three. Conowingo and Safe Harbor dams were completed in 1928 and 1931, respectively. The original volumes of the impoundments, in billion cubic feet, were approximately 6.5 (Lake Clarke), 2.6 (Lake Aldred), and 10 (Conowingo Reservoir).

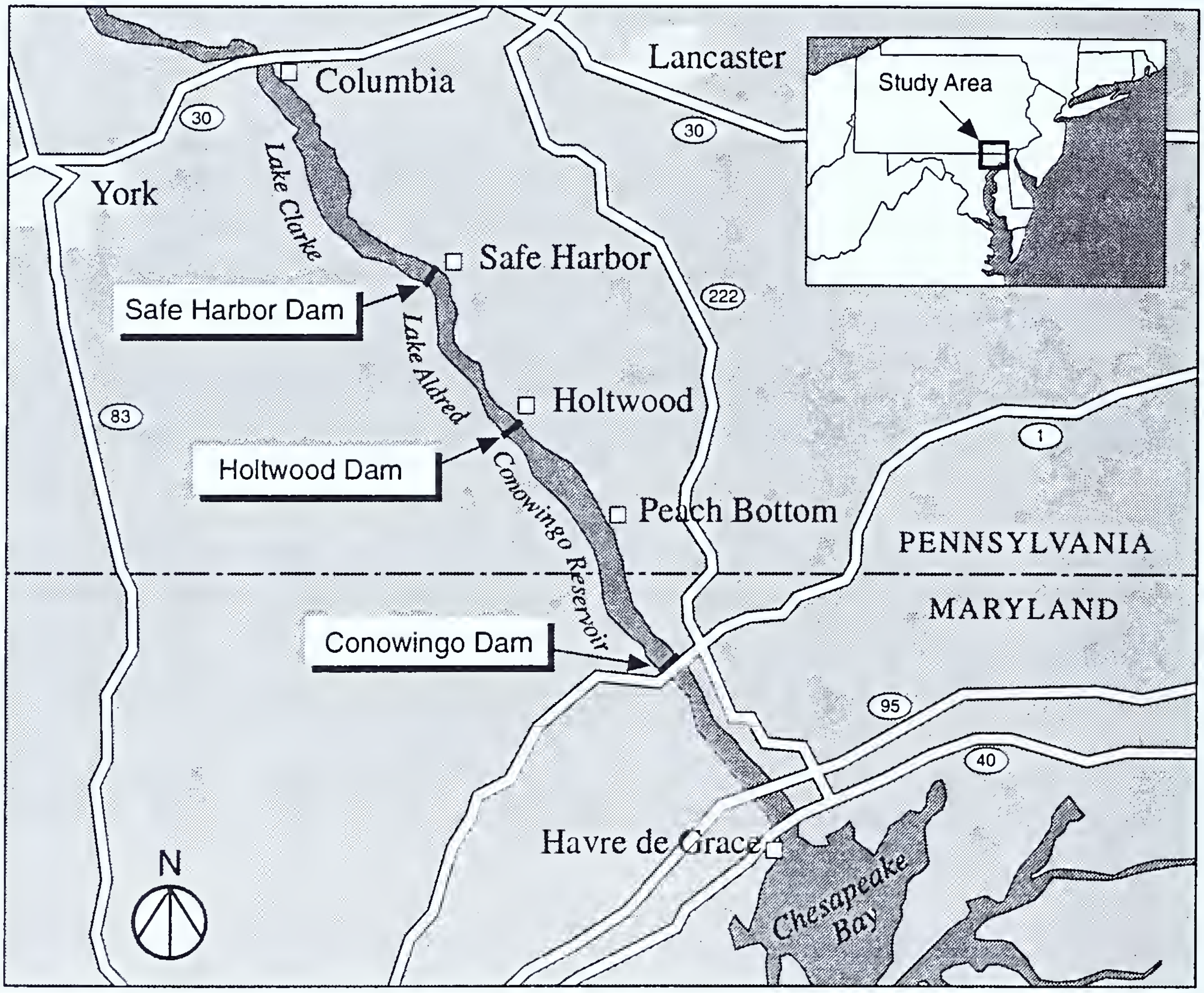


FIGURE 1. The lower Susquehanna reservoir system.

Overview of the USGS Draft Report

Before proceeding, we should emphasize that the USGS report on which we will comment is only in draft form and is currently under revision. This draft report, however, has been widely circulated for comment, and public presentations of results and conclusions from it have been made. Some of these results and conclusions have been incorporated into newspaper articles and widely disseminated among the general public. Consequently, despite the draft status of the report, it has already received widespread public exposure and probably has influenced both public opinion and public policy. For these reasons, we believe that discussion of several issues raised in the report is warranted.

The USGS draft report (Hainly et al., draft) provides five main types of information about the reservoir system. These include estimates of (1) average annual inputs and outputs of sand, silt, clay, and total sediment, (2) quantities of stored sand, silt, clay, and total sediment, (3) quantities of stored nitrogen, phosphorus, and selected metals, and (4) bed elevations and cross-sectional areas of the impoundments. They also include (5) results of implementing the Corps of Engineers' HEC-6 model (USACE 1991) in an attempt to predict changes in sediment deposition and scour under different flow conditions, including major floods.

The three main goals of the USGS study were to estimate the steady-state sediment-storage capacity of the reservoir system, to estimate the additional time required for this steady state to be achieved, and to make quantitative, model-based predictions of sediment transport through the reservoir system. Reliable results of these kinds would be useful in predicting future sediment and nutrient discharges to Chesapeake Bay, and in evaluating basin management options to meet provisions of the Chesapeake Bay Agreement.

The basic idea underlying the study is that, as long as the reservoirs contain less sediment than their steady-state capacity, the resulting net deposition will continue to reduce the Susquehanna's discharge of sediment and particle-bound nutrients to the Chesapeake, compared to what that discharge would be if the reservoirs were not present. Once they reach steady state, however, this reduction will cease and the Susquehanna's nutrient discharge will accurately reflect the contribution of its drainage basin. If we know the steady-state capacity, how much sediment is currently stored in the reservoirs, and what the annual rate of net deposition is, then we can make a rough prediction of how much time will be required to reach steady state. In addition, the nutrient content of stored sediment is potentially important in predicting the impact of major storms, which scour some of the stored sediment and associated nutrients from the reservoir system and transport them to the Bay.

In the draft report, Hainly et al. estimated average total sediment and nutrient inputs to the three reservoirs over the period from 1964 through 1989. Average sediment and nutrient outputs from the reservoir system were estimated over the period from 1985 through 1989, using data collected at Conowingo Dam. The resulting estimates of average inputs, outputs, net deposition, and trap efficiency are listed in Table 1.

The authors also estimated the amount of sediment currently stored in the three impoundments. In addition, they provided two crude estimates of the steady-state sediment capacity of Conowingo Reservoir, based on educated guesses as to the elevation of the sediment-water interface at steady-state (neither of which is technically defensible). These yielded two crude estimates of remaining capacity (= steady-state capacity - amount currently stored). Assuming that Lake Clarke and Lake Aldred are indeed at steady state, that the estimates of average annual net deposition in Table 1 are accurate and continue to be so until Conowingo reaches steady-state, and that no major floods occur before that time, the authors estimated that it will take roughly 15 to 20 years for Conowingo Reservoir to reach steady-state. (The importance of major floods is discussed below.) No likely error intervals for these estimates were provided.

TABLE 1. Estimates of average sediment and nutrient inputs, outputs, and net deposition, based on Hainly et al. (draft).

Constituent	Average annual load (tons)			
	Input	Output	Deposition	% Trapped
Sand	490,000	0	490,000	100
Silt	1,500,000	450,000	1,050,000	70
Clay	1,300,000	450,000	850,000	65
Total sediment	3,290,000	900,000	2,390,000	73
Nitrogen	77,000	73,500	3,500	5
Phosphorus	4,550	2,550	2,000	44

It is probably true that Lake Clarke and Lake Aldred are near steady state with respect to total stored sediment (representing approximately 44% of the original volume, in the case of Lake Clarke). As we will show below, however, the high degree of annual variation in sediment transport, combined with the small number of measurements, makes the estimates of average annual net deposition in Table 1 unreliable as predictors of future deposition. Moreover, since the trap efficiency of the reservoir system should decline as stored sediment increases, current annual accumulation should be smaller than during the years on which the USGS estimates are based (1964 through 1989) and should become progressively smaller in the future. Thus, the assumption of linear filling which underlies the USGS estimates of time until reaching capacity is probably incorrect, resulting in overestimation of the current and future rates of filling and underestimation of the time to reach steady state. The effect of major floods on reservoir filling is also not properly accounted for (see below), further biasing the estimates toward rapid filling and short time to reach steady state.

Successful implementation of the HEC-6 sediment transport model would have provided a more credible basis for estimating the time to reach steady state. Unfortunately, the attempt to calibrate the model using data for 1987 resulted in a major discrepancy between predicted and measured trap efficiency (33.8% predicted versus 76.5% measured). To eliminate this error, it was necessary to grossly distort the measured relationship between river discharge and the size-distribution of suspended particles, clearly revealing the model's inadequacy for representing sediment transport in this system.

We will comment no further on the HEC-6 modeling results, or on the USGS estimates of when Conowingo Reservoir will reach its steady-state level of sediment storage. The remainder of this report will focus on the following four issues in the USGS draft report:

1. What is the sediment trap efficiency of the reservoir system?
2. What does "average" mean?
3. What is the relationship between particle size, sediment transport, and nutrient transport through the reservoir system?
4. What is the nature of the steady state for the reservoir system?

What is the Trap Efficiency of the Reservoir System?

One of the central issues in the USGS report is the following: on average, what percentage of the sediment carried into the reservoir system is trapped? Based on estimates of average clay, silt, and sand inputs from 1964 through 1989 (3.3×10^6 tons per year), and average clay, silt, and sand outputs from 1985 through 1989 (0.9×10^6 tons per year), the authors arrive at an estimated trap efficiency of about 73% (Table 1). Several other estimates are available in the literature (Table 2). These differ widely, ranging from a low of - 192% (pronounced net scouring) to a high of +78% (substantial net deposition).

The available estimates of average trap efficiency are plagued by the fact that no statistical confidence intervals are provided. Gross et al. (1978) noted this same problem with the annual sediment discharge data used to calculate trap-efficiency. These authors expressed the opinion that the order of magnitude is probably correct, but that it is questionable whether even one significant digit can be considered statistically significant. According to this view, input and output estimates of 2×10^6 and 1×10^6 tons per year (for example) do not provide strong evidence that input actually exceeded output, even though one estimate is twice the other. This view, however, is based merely on professional judgment and is not technically defensible. In the absence of valid statistical confidence intervals, there is simply no objective way to assess how close any of the estimates of trap efficiency is likely to be to the true value for a given year or to the long-term average.

What Does "Average" Mean?

The pronounced difference in estimates of average trap efficiency have several sources. One of these concerns the definition of "average". Some examples from Table 2 will make the problem clear.

Gross et al. (1978) presented paired input-output estimates for 8 of the 11 years from 1966 through 1976 (second through ninth lines in Table 2). This period includes two major floods with peak discharges at Conowingo exceeding 700,000 cfs. The estimate of Ott et al. (1991) is based on data for the five years from 1985 through 1989, a period during which the peak discharge at Conowingo was only 403,000 cfs. The USGS study estimated average sediment input from data covering the 26-year period from 1964 through 1989, but estimated average output from data covering only the 5-year period from 1985 through 1989, thus including major floods in input estimates but not in output estimates. McLean and Summers (1990) based their estimate on a mass-balance study of particle-bound radionuclides released from the Peach Bottom Atomic Power Station over the 7-year period from 1981 through 1987, during which the peak discharge at Conowingo was 501,000 cfs.

The magnitude of floods is crucial to determining sediment output from the reservoirs. Historically, most of the sediment transported to the upper Chesapeake by the Susquehanna River was carried there by a small number of the largest floods. For example, based on dated sediment cores, Hirschberg and Schubel (1979) estimate that 50% of the sediment in the extreme upper Chesapeake came from just two floods: one in 1936 and one in 1972. Additional important contributions were probably made by several other floods whose peak discharges at Conowingo were well in excess of 400,000 cfs. Studies of sediment geochemistry corroborate

TABLE 2. Estimates of trap-efficiency of the lower Susquehanna reservoir system

Percent retention	Study period	Comments	Source
40	1962 to 1967		Williams & Reed (1972)
53 (67)*	1966	Inflow measured at Harrisburg	Biggs (1970)
65 (75)	1967		Schubel (1968)
45 (62)	1970		Gross et al. (1978)
29 (50)	1971		Gross et al. (1978)
-192 (-104)	1972	Tropical Storm Agnes occurred	Schubel (1974)
63 (74)	1973		Palmer et al. (1975)
53 (67)	1974		Palmer et al. (1975)
-189 (-103)	1975	Tropical Storm Eloise occurred	Gross et al. (1978)
45 (66)	1979 to 1981		Lang (1982)
66	1985		Ott et al. (1991)
72	1986		Ott et al. (1991)
78	1987		Ott et al. (1991)
76	1988		Ott et al. (1991)
69	1989		Ott et al. (1991)
5 to 20	1981 to 1987		McLean & Summers (1990)

* The original study estimated input based on sediment discharge at Harrisburg. The number in parentheses is an adjustment assuming the Susquehanna discharge is 70% of the total input to the reservoirs, based on data in Ott et al. (1991).

the dominant role of major floods in transporting sediment to the Chesapeake. Trace-metal ratios in bed sediments from the upper Bay are markedly different from those in suspended sediment from the Susquehanna during non-storm flows but resemble the ratios observed during storms (Helz et al. 1985, Helz and Sinex 1986).

Thus, the flow conditions which are the principal determinant of how much sediment and particle-bound nutrients are transported to the Chesapeake comprise major floods with multiple-year recurrence intervals. Averages based on measurements taken over different periods of 5 or 6 years or less are bound to vary widely, depending on the magnitude of the largest floods which happened to occur. Periods of this length are simply too short to yield reliable estimates of average sediment discharge from the reservoirs, because the degree of temporal variability is too large.

To make this argument somewhat more concrete, consider the problem of determining how many measurements of annual sediment discharge at Conowingo must be made so that, with 90% confidence, the sample average $\overline{X}$ will lie within a fraction p of the true but unknown mean μ. (For the purpose of illustration, we here accept the assumption of Hainly et al. that the true mean is constant during the course of reservoir filling.) A list of 18 such measurements appears in Table 3. These data are highly non-Gaussian, even if log-transformed, so the usual methods of

estimating confidence intervals are not applicable. Using Chebychev's inequality instead yields the following bound on the sample size n:

$$n \geq \frac{10}{p^2} (\sigma / \mu)^2,$$

where σ is the standard deviation of a single observation and σ/μ is the coefficient of variation. For the Conowingo discharge data, the coefficient of variation is about 2.4. This indicates substantial variability. If we want $\overline{X}$ to fall within plus or minus 10% of the true mean (implying $p = 0.1$), a sample of more than 2000 observations is necessary. If we are satisfied with $\overline{X}$ lying within only plus or minus 50% of the true mean ($p = 0.5$), a sample of more than 90 is required. These estimates are somewhat conservative, but as shown in Figure 2, plotting a running average of the measurements in Table 3 (which should converge to μ as $n \to \infty$) indicates that a sample size of 18 is not nearly large enough to trust $\overline{X}$ as an estimate of μ.

Beyond being simply unreliable, estimates of average trap efficiency based on periods which do not include major floods are almost certainly biased in the direction of overestimating efficiency. The reason is that moderate to high discharges transport sediment more efficiently through riverine portions of the Susquehanna than through impoundments, while the reverse is true at very high discharges (because the large amount of sediment stored in the reservoirs is then mobilized). For example, as illustrated in Figure 3, the relationship between the logarithm of suspended sediment concentration and the logarithm of water discharge is approximately linear over the entire range of measurements in the Susquehanna at Harrisburg. In contrast, the logarithm of suspended sediment concentration is unrelated to discharge at Conowingo until discharge exceeds approximately 10^5 cfs. This phenomenon was also noted by Gross et al. (1978). The implication is that moderate to high discharges will carry more sediment into the reservoir than out. Output begins to exceed input, however, at discharges of approximately 4×10^5 cfs (Lang 1982).

Discharges well in excess of this threshold can cause sediment output to greatly exceed input, as happened during the floods of 1972 and 1975 (peak discharges at Conowingo of approximately 11.3×10^5 and 7.10×10^5 cfs; USGS 1976). Gross et al. (1978) estimate that, during tropical storm Agnes, the Susquehanna transported 8.4×10^6 tons (7.6×10^6 metric tons) of sediment past Harrisburg, Pennsylvania, while 33×10^6 tons (30×10^6 metric tons) were discharged from Conowingo Reservoir. Assuming Harrisburg sediment discharge is 70% of the total input to the three lower Susquehanna reservoirs (based on Ott et al. 1991), the total input was approximately 12×10^6 tons. These estimates suggest that 21×10^6 tons of sediment were scoured from the reservoir system, representing approximately 10% of total stored sediment prior to the storm (based on data supplied by Susquehanna Electric Company, Pennsylvania Power and Light Company's Holtwood Operations, and Safe Harbor Water Power Corporation). Since tropical storm Agnes produced the highest instantaneous flow ever recorded on the Susquehanna, 10% of stored sediment is probably the highest percentage scoured in any storm to date.

Given the crucial role of major storms in transporting sediment, it is likely that both the Ott et al. (1991) and USGS estimates of trap efficiency overestimate the true mean efficiency, even if we assume the true mean remains constant instead of decreasing during reservoir filling.

TABLE 3. Sediment discharge at Conowingo

Discharge (million tons/year)	Year	Source
0.8	1966	Biggs (1970)
0.7	1967	Schubel (1968)
0.35	1969	Schubel (1972)
1.2	1970	Gross et al. (1978)
1.1	1971	Gross et al. (1978)
36	1972	Schubel (1974)
1.3	1973	Schubel (1974)
0.9	1974	Gross et al. (1978)
12	1975	Gross et al. (1978)
1.3	1976	Gross et al. (1978)
0.43	1985	USGS (1986)
1.3	1986	USGS (1987)
0.69	1987	USGS (1988)
0.49	1988	USGS (1989)
0.85	1989	USGS (1990)
0.58	1990	USGS (1991)
0.96	1991	USGS (1992)
0.43	1992	USGS (1993)

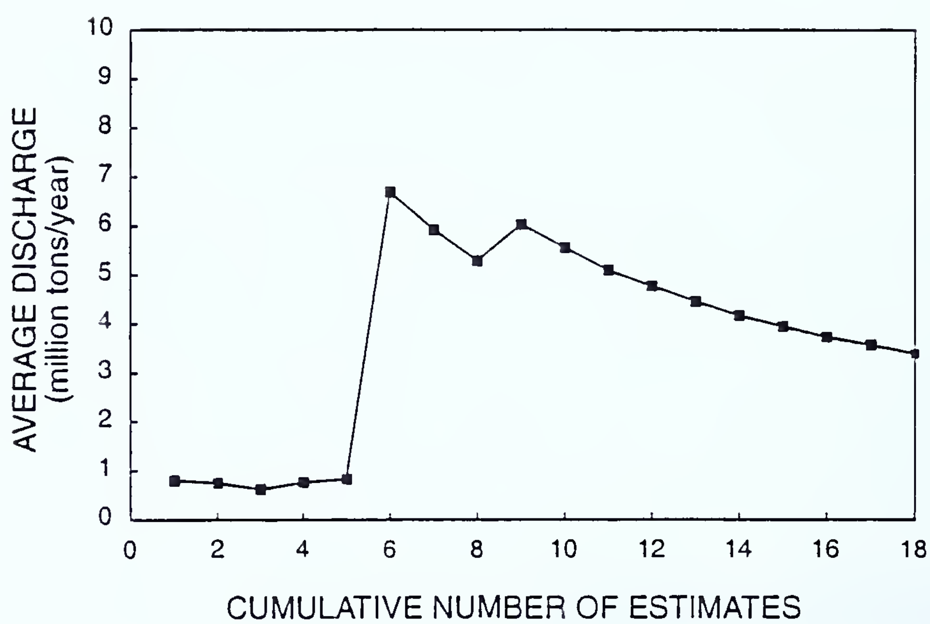


FIGURE 2. Running average of the sediment discharge values from Table 3.

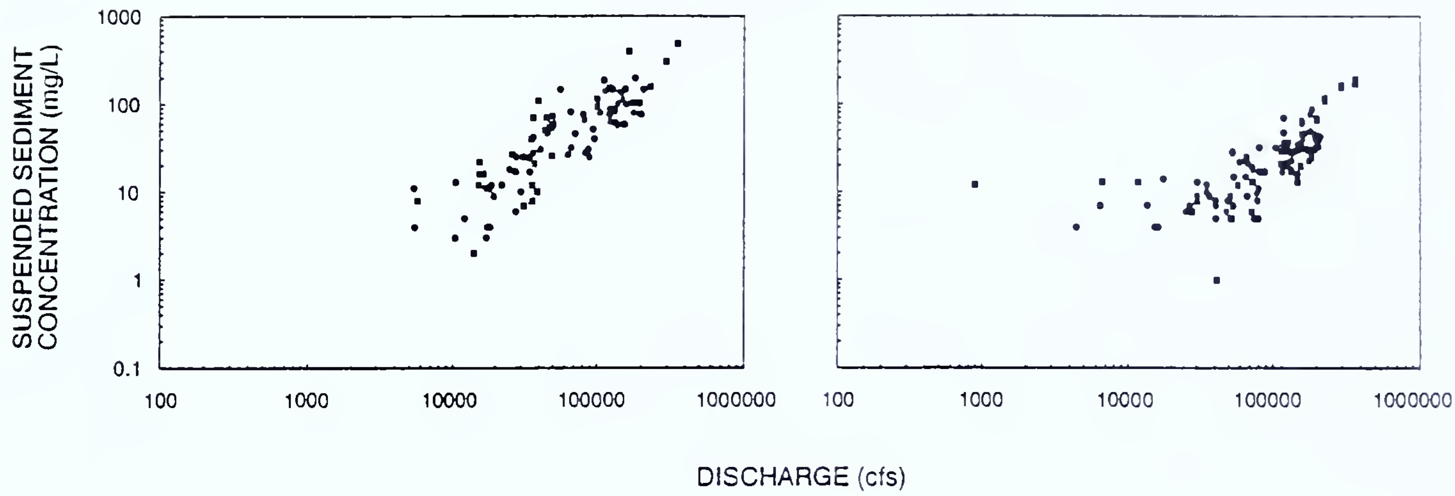


FIGURE 3. The relationship between discharge and the concentration of suspended sediment for the Susquehanna River at Harrisburg (left) and Conowingo Dam (right). Data are from USGS Water Resources Data reports.

The basis for the USGS estimate is particularly dubious, because it includes the elevating effect of several major floods on average sediment input to the reservoirs but excludes their effect on average output. This bias leads to an underestimate of average sediment and nutrient discharge to the Chesapeake, and of the time likely to be required for Conowingo Reservoir to reach steady state.

What is the Relationship Between Particle Size, Sediment Transport, and Nutrient Transport?

Another source of difference among available estimates of trap-efficiency is the effect of particle size on sediment transport. This seems to be particularly important in accounting for the relatively low estimates of McLean and Summers (1990). These authors, in effect, used radionuclides released from the Peach Bottom Atomic Power Station as tracers for studying particle transport. The radionuclides (^{60}Co, ^{134}Cs, ^{137}Cs, and ^{65}Zn) associate primarily with fine particles, especially clay (Nelson et al. 1966, Lick 1982b, Eisenbud 1987), so the resulting estimates of percentage retention apply mainly to the clay/silt fraction. Since coarser particles would have a higher percentage retention, the estimates are probably biased with respect to total sediment retention.

With respect to particle-bound nutrients, however, the estimate of McLean and Summers may actually be more appropriate than estimates which include sand and coarser particles. This is true in particular of phosphorus, most of which is transported in the particulate phase (e.g., Fishel 1984 estimated that 84% of the total phosphorus transported past Harrisburg from April 1980 through March 1981 was particulate; data in the Ott et al. report suggest that roughly 70% is particulate, on average). In this connection, it is interesting to note that the study of Ott et al. (1991) estimated the trap-efficiency to be roughly 70% for total sediment but only about 40% for

phosphorus. Assuming at least 70% of phosphorus is particulate, one would expect a trap-efficiency of at least 50% if particulate phosphorus were evenly distributed among all sediment fractions. Much less nitrogen is retained, because most of it is transported in the dissolved phase (e.g., the Fishel study estimated that 76% of total nitrogen was dissolved; data in the Ott et al. study suggest that nearly 90% is dissolved, on average). The study of Ott et al. estimated a trap efficiency of about 3% for total nitrogen, suggesting that the reservoir system has only a very small effect on transport of this nutrient, which appears to be the key determinant of primary productivity in the Chesapeake.

Not only is the proportion of clay and silt trapped smaller than the proportion of sand, but in the reservoir beds, these finer particles undoubtedly have higher turnover and resuspension rates. This means that these particles will be more easily mobilized by high flow conditions. One would therefore expect output to begin exceeding input at lower, more frequently occurring discharges than for sand.

Unfortunately, while transport of fine particulates is clearly a key to understanding the impact of the reservoirs on nutrient delivery to Chesapeake Bay, the basic principles governing this transport are poorly understood. The inadequacy of current knowledge for predicting the transport of fine sediment is a common theme in the applied literature on environmental modeling. For example, this is one of the central problems limiting our ability to accurately predict the transport of particle-bound contaminants in the Great Lakes (e.g., Lick 1982a, 1982b). It has also been identified as a central problem limiting our understanding of the transport of particulate organic matter in rivers and streams (e.g., Cushing et al. 1993). Given this, the failure of the USGS HEC-6 modeling effort comes as no surprise.

What is the Nature of the Steady State?

The final issue we wish to address is the nature of the steady state (i.e., asymptotic dynamics) for reservoirs on the lower Susquehanna. As the USGS report notes, available data appear to indicate that the total bed-sediment loads in Lake Clarke and Lake Aldred currently are neither increasing nor decreasing, but that net accumulation is still occurring in Conowingo Reservoir. There is concern that non-flood sediment and nutrient transport to Chesapeake Bay will increase as Conowingo approaches steady state. There is also concern that the increased load of stored sediment will pose a greater threat to the Bay when major floods occur. The implied view of the reservoir system's ultimate effect on sediment and nutrient delivery to the Bay is thus somewhat bleak.

There is, however, an alternative and perhaps more balanced view. First, what actually will be happening as net deposition in Conowingo Reservoir declines is that there will be a return to the natural non-flood discharges of sediment and nutrients. In other words, these discharges will once again accurately reflect the loadings from the drainage basin, just as they did before the reservoirs were built. These levels are determined, not by the reservoirs, but by the character of the watershed and by land-use practices therein.

Second, it is true that sediment and nutrients stored in the reservoirs result in a larger pulse of these materials to the Bay when major floods occur, compared to the hypothetical situation without the reservoirs. But it is likewise true that, following such a flood, a decrease in

discharge of sediment and nutrients from the reservoirs occurs as net deposition replaces the scoured sediment. Thus, each major pulse is followed by a period during which sediment and nutrients are delivered to the Bay at lower rates than would be observed without the reservoirs. In effect, the reservoirs "take back" the storm-related pulse during the ensuing non-storm period. This fact is ignored in the USGS report and in several newspaper accounts based on it (e.g., *Bay Journal*, June, 1992; Lancaster *New Era*, 21 November 1992), which focus only on the pulse.

To arrive at a proper understanding of the reservoir system's long-term impact on sediment and nutrient transfer to the Chesapeake, it is necessary to combine three concepts into a single overall view of the system: (1) approaching the non-storm steady-state level of stored sediment during periods without major floods, (2) net scouring of stored sediment during major floods, and (3) net deposition following scouring events. While it is true that net deposition would cease if the reservoir system reached the non-flood steady state, it is also true that major storms will sporadically remove stored sediment and push the reservoir system below the non-flood steady state. That is why net deposition will never permanently cease, nor will stored sediment ever permanently remain at the non-flood steady state.

Thus, the steady-state condition for the reservoir system does not consist of sediment storage at the non-flood steady state with zero net deposition. The steady state will in fact not be steady at all. Instead, it should be thought of as the stationary probability distribution for the state of a stochastic process. In the long term, sediment dynamics in the reservoir system will comprise periods of gradual accumulation, punctuated by episodic flood-driven scouring (Fig. 4). The timing and magnitude of these scouring events cannot be predicted with any certainty, because both are stochastic phenomena. At best, we can predict their probability distributions. But we can predict with confidence that the long-term average rate of net deposition in the reservoirs will be zero. We can also predict with confidence that the long-term average level of stored sediment in the reservoirs will be below their non-flood steady-state levels, due to the sporadic scouring effect of major floods.

The basic point is that, under steady-state conditions, the reservoirs will simply have no effect on the ultimate fate of sediment transported by the Susquehanna. Over time-intervals of sufficient length, there will be no net retention of sediment between Columbia, Pennsylvania, and Conowingo, Maryland, just as if the reservoirs were not present. The reservoirs will, however, continue to alter the timing of sediment delivery to the Bay, with more being delivered during major floods and less during the ensuing non-flood periods. Thus, the reservoirs will have no effect on long-term average delivery but will increase the variance about that average.

What this means is that measures to reduce long-term average sediment and nutrient discharges from the Susquehanna should be focused entirely on land-use practices and other controllable sources of sediment and nutrients in the watershed. These average discharges will be the same as if the reservoirs were not present.

There remains the question as to what effect the increased variance in discharges has on ecosystem structure and function in the Chesapeake. A detailed discussion of this issue is beyond the scope of the present report, but we point out that it has several facets which must be addressed in any balanced assessment of ecosystem impacts. First, it is not sufficient to consider only the effect of sediment and nutrient pulses; the subsequent periods during which net

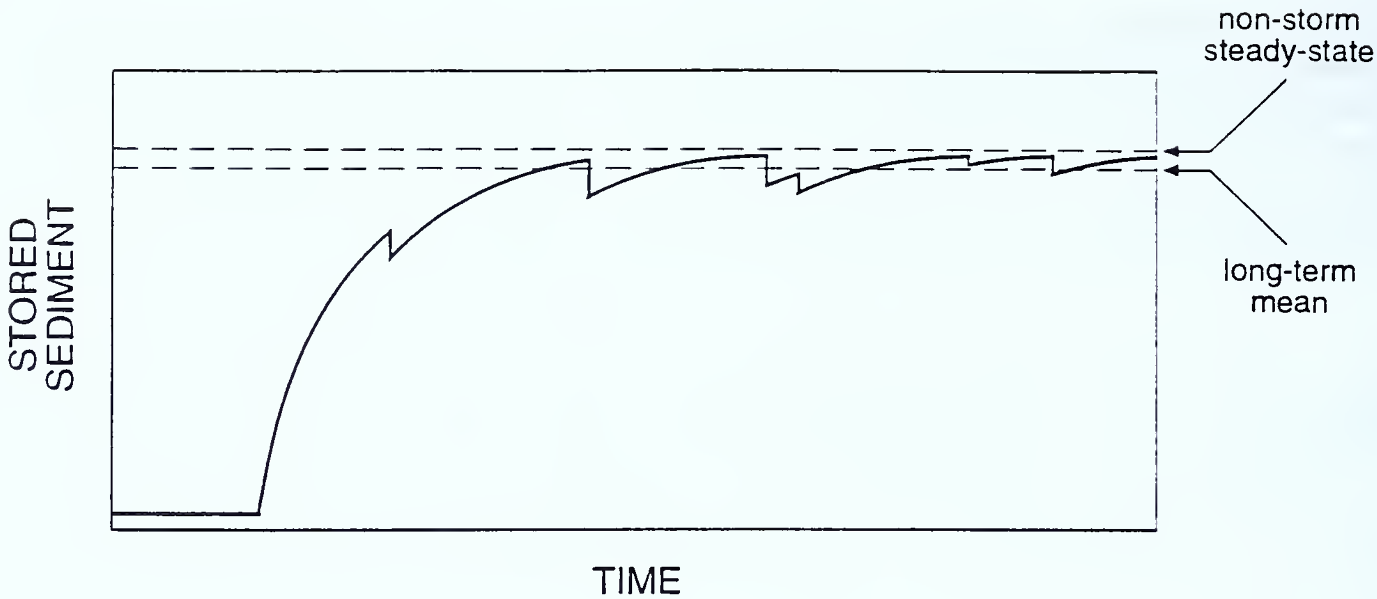


FIGURE 4. Schematic of the long-term temporal dynamics of stored sediment in the reservoir system. Periods of gradual accumulation (net deposition) are punctuated by scouring events (major floods) which remove small fractions (≤10%) of the sediment stored in the reservoirs. The quantity of stored sediment is therefore a stochastic process; "steady state" properly refers to the stationary probability distribution for this process. Note that the long-term mean sediment content is less than the steady state that would exist if there were no major storms.

deposition in the reservoirs reduces sediment and nutrient discharges below the long-term average must also be considered. Second, the quantity of sediment and nutrients actually derived from the three reservoirs, rather than from other reaches of the lower Susquehanna or from its flood plain, must be more accurately estimated than in past major floods so the impact of the reservoirs per se can be isolated from the impacts of other sources of sediment and nutrients. Finally, the contribution of the numerous estuaries bordering the Chesapeake must be considered in addition to that of the Susquehanna River. Storm-related scouring of sediment stored in these estuaries has thus far been ignored in sediment budgets for the Bay (Hobbs et al. 1992), despite the fact that resuspension and transport of bed sediment are known to be signficant processes in other partially mixed estuaries (e.g., Uncles et al. 1985). As indicated above, the Chesapeake's peripheral estuaries are even more efficient sediment traps than the lower Susquehanna reservoir system, and they contain large stores of sediment and nutrients. The relative importance of storm-related increases in sediment and nutrient loadings from the reservoir system can be judged accurately only if the total increase in loadings from all sources is known.

BIBLIOGRAPHY

Adams, F. S., H. Cole, and L. B. Massie. 1973. Element constitution of selected aquatic vascular plants from Pennsylvania: submersed and floating leaved species and rooted emergent species. Environ. Pollut. 5:117-147.

Anonymous. 1937. Condition of standing timber in the reservoir of the Conowingo Hydro Plant. Report prepared by Philadelphia Electric Company.

———. 1946. Supplemental report of slate dust deposit, York County, Pa. Report to Philadelphia Electric Company.

———. 1950. Sedimentation in Conowingo Lake. Philadelphia Electric Company report.

———. 1968. Study of maximum water level at Peach Bottom Power Plant site. Report prepared for Philadelphia Electric Company by: Tippetts-Abbet-McCarthy-Stratton Engineers and Architects.

———. 1985. Water quality studies relative to objectives 1 to 3 of Article 34 for the Conowingo Hydroelectric Station. Report by RMC Environmental Services, prepared for Philadelphia Electric Company.

Biggs, R. B. 1970. Geology and hydrology. Pages 7-15 *in* Gross physical and biological effects of overboard spoil disposal in upper Chesapeake Bay. Natural Resources Institute Special Publication No. 3, University of Maryland.

———. 1970. Sources and distribution of suspended sediment in northern Chesapeake Bay. Marine Geology 9:187-201.

Biggs, R. B. and B. A. Howell. 1984. The estuary as a sediment trap: alternate approaches to estimating its filtering capacity. Pages 107-128 *in* V. S, Kennedy, ed. The estuary as a filter. Academic Press, New York.

Bollinger, S. W. 1991. Water quality of interstate streams in the Susquehanna River basin, monitoring report No. 4, water year 1990 (October 1, 1989 - September 30, 1990). Susquehanna River Basin Commission, Publication No. 140.

———. 1992. Water quality of interstate streams in the Susquehanna River Basin, Monitoring Report No. 5, October 1, 1990 - June 30, 1991. Susquehanna River Basin Commission, Publication No. 146.

Burns, M. M., and R. C. MacArthur. 1993. Sediment deposition in Jennings Randolph reservoir, Maryland and West Virginia. Proceedings - National Conference on Hydraulic Engineering, part 2, 1993. Published by ASCE, New York.

Burton, G. A. 1991. Assessing the toxicity of freshwater sediments. Environmental Toxicology and Chemistry 10:1585-1627.

Clark, L. J., D. K. Donnelly, and O. Villa. 1973. Summary and conclusions from the forthcoming Technical Report 56, "Nutrient Enrichment and Control Requirements in the Upper Chesapeake Bay". EPA-903/3-73-002-a.

Clark, L. J., V. Guide, and T. H. Pheiffer. 1974. Summary and conclusions: Nutrient transport and accountability in the lower Susquehanna River basin. EPA-903/9-74-014.

Cohn, T. A., L. L. DeLong, E. J. Gilroy, R. M. Hirsch, and D. K. Wells. 1989. Estimating constituent loads. Water Resour. Res. 25:937-942.

Crook, W. T. 1951. Conowingo River bed silt survey, October 1951. Holtwood Steam Station, Pennsylvania Water and Power Co. report.

Cushing, C. E., G. W. Minshall, and J. D. Newbold. 1993. Transport dynamics of fine particulate organic matter in two Idaho streams. Limnology and Oceanography 38:1101-1115.

Delfino, J. J., and R. G. Otto. 1986. Trace metal transport in two tributaries of the upper Chesapeake Bay: the Susquehanna and Bush rivers. Marine Chemistry 20:29-44.

Domotor, S. L. and R. I. McLean. 1989. Environmental radionuclide concentrations in the vicinity of the Peach Bottom Atomic Power Station. Power Plant and Environmental Review Division report PPER-R-11, Anapolis, Maryland.

Donoghue, J. F., O. P. Bricker, and C. R. Olsen. 1989. Particle-borne radionuclides as tracers for sediment in the Susquehanna River and Chesapeake Bay. Estuarine, Coastal and Shelf Science 29:341-360.

Eaton, A. 1979. The impact of anoxia on Mn fluxes in the Chesapeake Bay. Geochim. Cosmochim. Acta 43:429-432.

Eaton, A., V. Grant, and M. G. Gross. 1980. Chemical tracers for particle transport in the Chesapeake Bay. Estuarine and Coastal Marine Science 10:75-83.

Edwards, R. E. 1986. Chesapeake Bay data base: Documentation of historical data in the lower Susquehanna River basin. Susquehanna River Basin Commission, Publication No. 106.

Edwards, R. E., and E. E. Seay. 1987. Nutrient trends and land use changes in selected watersheds in the lower Susquehanna River basin. Susquehanna River Basin Commission publication no. 112.

Eisenbud, M. 1987. Environmental radioactivity from natural, industrial, and military sources. 3rd ed. Academic Press, Orlando.

Engman, E. T., L. H. Parmele, and W. J. Gburek. 1974. Hydrologic impact of tropical storm Agnes. Journal of Hydrology 22:179-193.

Fan, Shou-shan, ed. 1988. Twelve selected computer stream sedimentation models developed in the United States. Federal Energy Regulatory Commission, Washington, D. C.

Fishel, D. K. 1984. Water-quality and chemical loads of the Susquehanna River at Harrisburg, Pennsylvania, April 1980 to March 1981. USGS Water Resources Investigations Report 83-4164.

Flemer, D. A., and R. B. Biggs. 1971. Particulate carbon:nitrogen relations in northern Chesapeake Bay. Journal of the Fisheries Research Board of Canada 28:911-918.

Gross, M. G., M. Karweit, W. B. Cronin, and J. R. Schubel. 1978. Suspended sediment discharge of the Susquehanna River to norther Chesapeake Bay, 1966 to 1976. Estuaries 1:106-110.

Hainly, R. A., L. A. Reed, H. N. Flippo, and G. J. Barton. 1993. Deposition and simulation of sediment transport in the lower Susquehanna River reservoir system (draft). U.S. Geological Survey, Water Resources Investigation Report (draft).

Helz, G. R., and S. A. Sinex. 1986. Influence of infrequent floods on the trace metal composition of estuarine sediments. Marine Chemistry 20:1-11.

Helz, G. R., S. A. Sinex, K. L. Ferri, and M. Nicols. 1985. Processes controlling Fe, Mn, and Zn in sediments of northern Chesapeake Bay. Estuarine, Coastal and Shelf Science 21:1-16.

Hirschberg, D. J., and J. R. Schubel. 1979. Recent geochemical history of flood deposits in the northern Chesapeake Bay. Estuarine and Coastal Marine Science 9:771-784.

Hobbs, C. H., J. P. Halka, R. T. Kerhin, and M. J. Carron. 1992. Chesapeake Bay sediment budget. J. Coast. Res. 8:292-300.

Hollowell, J. R. 1987. Nutrient monitoring of the lower Susquehanna River and selected tributaries, October 1, 1984 - September 30, 1986: interim report. Susquehanna River Basin Commission publication no. 108.

Hooper, L. J. 1967. Flood routing for Conowingo Reservoir. Report prepared for Philadelphia Electric Company.

James, W. F., and J. W. Barko. 1993. Sediment resuspension, redeposition, and focusing in a small dimictic reservoir. Can. J. Fish. Aquat. Sci. 50:1023-1028.

Jordan, T. E., D. L. Correll, J. Miklas, and D. E. Weller. 1991. Longterm trends in estuarine nutrients and chlorophyll, and shortterm effects of variation in watershed discharge. Marine Ecology Progress Series 75:121-132.

Lane, R. A. 1937. Erosion or silting of reservoir of Conowingo Hydro Plant. Philadelphia Electric Company.

Lane, R. A., and R. E. Turner. 1943. Sedimentation in the Conowingo Reservoir and other reservoirs in the lower Susquehanna River. Philadelphia Electric Company report.

Lang, D. J. 1982. Water quality of the three major tributaries to the Chesapeake Bay: the Susquehanna, Potomac, and James rivers, January 1979 - April 1981. USGS Water Resources Investigations Publication 82-32.

Lick, W. 1982a. Entrainment, deposition, and transport of fine-grained sediments in lakes. Hydrobiol. 91:31-40.

———. 1982b. The transport of contaminants in the Great Lakes. Ann. Rev. Earth Planet Sci. 10:327-353.

Lietman, P. L., J. R. Ward, and T. E. Behrendt. 1983. Effects of specific land uses on nonpoint sources of suspended sediment, nutrients, and herbicides: Pequea Creek basin, Pennsylvania. USGS Water Resources Investigations Report 83-4113.

Lyon, W. A. 1988a. History of point source control of nutrients in Pennsylvania and other Chesapeake Bay states: Part II. Water Pollution Control Association of Pennsylvania Magazine 21:7-14.

———. 1988b. History of point source control of nutrients in Pennsylvania and other Chesapeake Bay state: Part I. Water Pollution Control Association of Pennsylvania Magazine 21:34-37.

Malone, T. C., L. H. Crocker, S. E. Pike, and B. W. Wendler. 1988. Influences of river flow on the dynamics of phytoplankton production in a partially stratified estuary. Marine Ecology Progress Series 48:235-249.

McDuffie, B., I. El-Barbary, G. J. Hollod, and R. D. Tiberio. 1978. Heavy metals in Susquehanna River bottom sediments: surficial concentrations, urban impacts, and transport mechanisms. Pages 467-469 *in* O. Hutzinger, I. H. van Lelyveld and B. C. J. Zoeteman, eds. Aquatic pollutants: transformation and biological effects. Pergamon, Oxford (UK).

McGeehan, K. A. 1989. Sediment budget for a small agricultural watershed. Water Pollution Control Association of Pennsylvania Magazine 22:14-19.

McHenry, J. R., J. C. Ritchie, and F. R. Schiebe. 1976. Estimating the suspended sediment load in reservoirs. Water Resources Bulletin 12:81-92.

McLean, R. I. 1989. PPER examines radionuclides in Conowingo Pond sediments. PPER/CBRM Power Plant Update 3:3-4.

McLean, R. I., and J. K. Summers. 1990. Evaluation of transport and storage of Co-60, Cs-134, Cs-137, and Zn-65 by river sediments in the lower Susquehanna River. Environ. Pollut. 63:137-153.

McLean, R. I., S. L. Domotor, J. K. Summers, V. A. Dickens, and C. R. Olsen. 1988. Radionuclide concentrations in Susquehanna River and Chesapeake Bay sediments: implications for transport and distribution of particle-reactive pollutants. Pages 157-169 *in* Understanding the estuary: advances in Chesapeake Bay research. Chesapeake Research Consortium, Gloucester Point, Virginia.

McLean, R. I., J. K. Summers, C. R. Olsen, S. L. Domotor, I. L. Larsen, and H. Wilson. 1991. Sediment accumulation rates in Conowingo Reservoir as determined by man-made and natural radionuclides. Estuaries 14:148-156.

McMorran, C. P. 1990. Water quality assessment report: Susquehanna River basin. Susquehanna River Basin Commission, Publication No. 130.

Mills, W. B., J. N. Dean, D. B. Porcella, S. A. Gherini, R. J. M. Hudson, W. E. Frick, G. L. Rupp, and G. L. Bowie. 1982. Water quality assessment: A screening procedure for toxic and conventional pollutants - Part 2. US EPA Report #EPA-600/6-82-004b; NTIS #PB83-153130., Athens, GA.

Mossman, D. J., R. E. Jensen, and J. M. Blancett. 1993. Mixing and transport. Water Environment Research 65:468-480.

Nelson, J. L., R. W. Perkins, J. M. Nielsen, and W. L. Haushild. 1966. Reactions of radionuclides from the Hanford reactors with Columbia River sediments. Pages 139-161 *in* Disposal of radioactive wastes into the seas, oceans, and surface waters. IAEA Proc. Ser., IAEA, Vienna.

Officer, C. B., D. R. Lynch, G. H. Setlock, and G. R. Helz. 1984. Recent sedimentation rates in Chesapeake Bay. Pages 131-157 *in* V. S. Kennedy, ed. The Estuary as a Filter. Academic Press, Orlando, FL.

Officer, C. B. and M. M. Nichols. 1980. Box model application to a study of suspended sediment distributions and fluxes in partially mixed estuaries. Pages 329-340 *in* V. S. Kennedy, ed. Estuarine perspectives. Academic Press, New York.

Ott, A. N. 1991. Nutrient loading status of the Conestoga River Basin, 1985-1989. Susquehanna River Basin Commission, Publication No. 133.

Ott, A. N., C. S. Takita, and S. W. Bollinger. 1989. Estimate of the occurrence and distribution of toxicants in streambed sediments of the Susquehanna River system. Susquehanna River Basin Commission, Publication No. 123.

Ott, A. N., C. S. Takita, R. E. Edwards, and S. W. Bollinger. 1991. Loads and yields of nutrients and suspended sediment transported in the Susquehanna River basin, 1985-1989. Susquehanna River Basin Commission, Publication No. 136.

Palmer, H. D., J. R. Schubel, and W. B. Cronin. 1975. Estuarine sedimentology. Pages 4.1-4.63 *in* T. Munson, ed. Upper Bay survey report. Westinghouse Electric, Annapolis, Maryland.

Pennsylvania Department of Environmental Resources. 1994. Pennsylvania's draft nutrient reduction strategy for the Susquehanna and Potomac River basins. PADER report no. 1656-3/94.

Ritchie, J. C., J. R. McHenry, and F. R. Schiebe. 1978. The vertical distribution of suspended sediments in reservoirs. Journal Water Pollution Control Federation, April 1978:734-738.

Rose, K. A., R. I. McLean, and J. K. Summers. 1989. Development and Monte Carlo analysis of an oyster bioaccumulation model applied to biomonitoring data. Ecological Modelling 45:111-132.

Schubel, J. R. 1968. Suspended sediment discharge of the Susquehanna River at Havre de Grace, Maryland, during the period, 1 April 1966 through 31 March 1967. Ches. Sci. 9:131-135.

———. 1972. Suspended sediment discharge of the Susquehanna River at Conowingo, Maryland, during 1969. Ches. Sci. 13:53-58.

———. 1974. Effects of tropical storm Agnes on the suspended solids of the northern Chesapeake Bay. Marine Science 4:113-132.

———. 1975. Suspended sediment in Chesapeake Bay. In: Proc. ASCE Specialty Conf. on Civil Engng. in the Oceans III, vol. 1, New York, Am. Soc. Civ. Engrs., pp. 245-264.

Schubel, J. R., and R. B. Biggs. 1969. Distribution of seston in upper Chesapeake Bay. Ches. Sci. 10:18-23.

Schubel, J. R., and D. W. Pritchard. 1985. Responses in the milieu and biology of upper Chesapeake Bay to bariations in discharge of the Susquehanna River. Estuaries 8:53A.

Seay, E. A. 1993. Managing sediments and nutrients in the Susquehanna River Basin: Plan of study. Susquehanna River Basin Commission, Publication No. 153.

Sherk, J. A. 1972. Current status of knowledge of the biological effects of suspended and deposited sediments in Chesapeake Bay. Ches. Sci. 13 (Supplement):S137-S144.

———. 1973. Current status of the knowledge of the biological effects of suspended and deposited sediments in Chesapeake Bay. Appendix C in Army Corps of Engineers Chesapeake Bay Existing Conditions Report, vol. 2, pp C172-C183.

Stumpf, R. P. 1988. Sediment transport in Chesapeake Bay during floods: analysis using satellite and surface observations. J. Coast. Res. 4:1-15.

Takita, C. 1984. Review of Pennsylvania's Comprehensive Water Quality Management Plan and Maryland's Section 208: Water Quality Management Plan for Interstate Streams. Susquehanna River Basin Commission publication no. 88.

Takita, C. S., and R. E. Edwards. 1993. Nutrient and suspended sediment loads transported in the Susquehanna River Basin, 1990-1991. Susquehanna River Basin Commission, Publication No. 150.

Tavolaro, J. J., and J. M. Mansky. 1984. Effects of dredging operations on nutrient and suspended sediment concentrations. NE Environ. Can. J. Fish. Aquat. Sci. 3:209-216.

Thornton, K. W., R. H. Kennedy, J. H. Carroll, and R. C. Gunkel. 1980. Reservoir sedimentation and water quality: an heuristic model. Manuscript.

Uncles, R. J., R. C. A. Elliott, and S. A. Weston. 1985. Observed fluxes of water, salt and suspended sediment in a partly mixed estuary. Estuarine, Coastal and Shelf Science 20:147-167.

United States Army Corps of Engineers (USACE). 1991. HEC-6: Scour and deposition in rivers and reservoirs — user's manual. Hydrologic Engineering Center report CPD-6, Davis, California.

United State Geological Survey (USGS). (various years) Water Resources Data for Maryland and Delaware, Volume 1.

United State Geological Survey (USGS). (various years) Water Resources Data for Pennsylvania, Volume 2.

Urban, J. B., and W. J. Gburek. 1989. Upland agricultural watershed contributions of nitrate to streamflow via subsurface flow. Abstract from conference, Ground Water Issues and Solutions in the Potomac River Basin / Chesapeake Bay Region, held in Washington, DC, 14-16 Mar 1989.

Ward, J. R. 1987. Surface-water quality in Pequea Creek basin, Pennsylvania, 1977-79. USGS Water Resources Investigations Report 85-4250.

Westrich, B. 1990. Aspects of modeling suspended sediment transport in nonuniform flows. Pages 97-105 *in* H. W. Shen, ed. Movable bed physical models. Kluwer Academic Publishers, Dordrecht, Netherlands.

Westrich, B., S. Al-Zoubi, and J. Mueller. 1992. Planning and designing a flushing channel for river reservoir sediment management. Pages 861-867 *in* P. Larsen and N. Eisenhauer, eds. Sediment Management. 5th International Conference on River Sedimentation, Karlsruhe, 1992. Proceedings, vol. 2.

Whaley, R. C. 1961. Conowingo Reservoir sedimentation and transparency. Chesapeake Bay Institute.

Williams, K. F., and L. A. Reed. 1972. Appraisal of stream sedimentation in the Susquehanna River basin. USGS Water-Supply Paper 1532-F.

Witzig, B. J. 1943. Sedimentation in reservoirs. Trans., A.S.C.E. 29:1047-1071.

Wood, E. F. 1979. A statistical approach to station discontinuance. Water Resour. Res. 15:1859-1866.

Zarn, B. 1992. Numerical simulation of sediment management in reservoirs planned along the River Rhine upstream of the Lake of Constance. Pages 853-860 *in* P. Larsen and N. Eisenhauer, eds. Sediment Management. 5th International Symposium of River Sedimentation, Karlsruhe, 1992, Proceedings, vol. 2.

Ziegler, C. K., and W. Lick. 1988. The transport of fine-grained sediments in shallow waters. Env. Geol. Wat. Sci. 11:123-132.

APPENDIX C

NUTRIENT AND SEDIMENT CONTROL SYSTEM USDA, NRCS
Environmental Quality Technical Note Number N4

United States
Department of
Agriculture

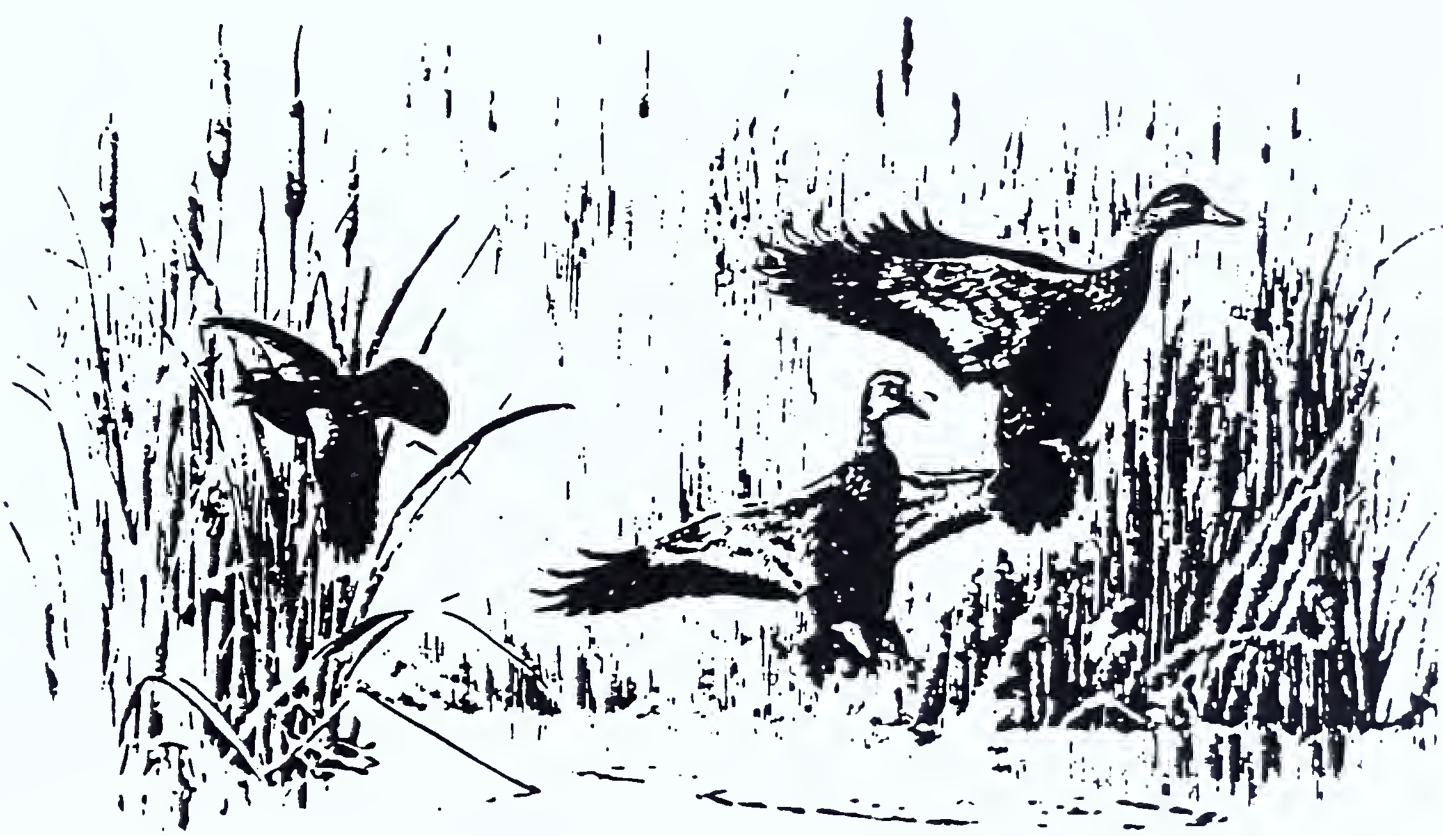
Soil
Conservation
Service

NNTC
Chester,
Pennsylvania

Environmental
Quality Technical
Note

Ecological
Sciences
Number N4

NUTRIENT AND SEDIMENT CONTROL SYSTEM



ENVIRONMENTAL QUALITY TECHNICAL NOTE NO. N4

NUTRIENT AND SEDIMENT CONTROL SYSTEM

GENERAL:

This technical note provides information on the planning, design, and operation and maintenance of a nutrient and sediment control system (NSCS) for the treatment of agricultural cropland nonpoint source runoff containing sediment and nutrients. The concept of this technical note has been described in a letter dated April 8, 1991 signed by Wildon J. Fontenot, National Environmental Coordinator, Ecological Sciences Division.

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SECTION 1 - INTRODUCTION

Agricultural and urban land uses contribute to nonpoint source pollution of lakes and streams resulting in impairments to fisheries, recreation, drinking water, irrigation water and aesthetic values. Reducing these sources of pollution is normally handled by treating the land with conventional conservation practices. Conventional practices can correct a water quality problem to an extent, but sometimes not to the extent desired. To further correct or improve the quality of the runoff, additional treatment may be needed to intercept and remove sediment, nutrients and other pollutants from the runoff before it enters a water body.

Prototype systems have been developed and installed by the USDA Soil Conservation Service in the State of Maine to supplement the needed land treatment. These Nutrient and Sediment Control Systems (NSCS) are in watersheds that drain potato fields. Each NSCS has, in series, a sediment basin, grassed buffer, two ponds (one vegetated shallow and the other deep) and a vegetated "polishing" area.

Approximately 90 percent of total phosphorus and suspended solids can be removed by the NSCS system during storm events. Similar results can be expected for nitrogen removal. Field scale data confirms literature reports and expected results. Successful implementation in the cold climate of northern Maine demonstrates that land treatment practices plus these treatment systems may provide effective nonpoint source reduction in other climatic regions.

In addition to cropland runoff, these systems have the potential for supplementing treatment in other areas, such as urban area runoff, barnyard runoff, milkhouse wastewater and aquacultural wastewater. The design, configuration, monitoring and management of NSCS's are discussed in this technical note.

On December 29, 1992, the U.S. Commissioner of Patents and Trademarks issued a United States patent to the United States Department of Agriculture for the NSCS (Patent Number 5,174,897). The patent covers the entire design and all ancillary components.

SECTION 2 - BACKGROUND

Aquatic ecosystems can be damaged by even small amounts of pollutants contained in runoff during storm events or from cumulative impacts due to long-term, low levels of pollutants. Nutrients, pesticides, and sediments are recognized for having long-term effects on lakes, streams and natural wetlands and their inhabitants. The sensitivity of aquatic ecosystems to pollution varies and may require more intensive pollution control systems to prevent offsite damage. For example, streams that are important for trout spawning and nursery areas are usually more ecologically sensitive to nutrient and sediment loadings than are streams where more tolerant bullhead, catfish, carp, and bass are dominant.

Although there are many soil and water conservation practices, it may not always be economical, practical, socially or culturally acceptable to avoid pollution in every situation.

Climatic factors often limit the selection of alternatives or the effectiveness of soil and water conservation measures and/or Best Management Practices for reducing nonpoint source pollution. In areas with short growing seasons, there is often inadequate time to establish effective winter cover crops. Also, fall tillage practices may be necessary for agronomic reasons.

In addition to the application of land treatment measures to avoid damage to sensitive aquatic ecosystems, there is a need to intercept and treat the runoff water that carries pollutants.

The NSCS is recognized for effectively reducing concentrations of pollutants from a variety of sources by intercepting and treating water (Hammer, 1989 and Cooper, et al., 1990). The NSCS's, described in this technical note, have been developed using "wetland/pond" technology (Walker, 1986). These systems are designed to intercept and treat runoff from cultivated cropland areas in northern Maine, (North 47 degrees; Latitude West 68 degrees Longitude) and are also proving to be effective in other parts of the country.

Northern Maine has a short growing season of less than 100 days and winter temperatures often reaching minus 40 degrees Fahrenheit. Runoff from intense rainfalls (one and one-half inches per hour) and snowmelt events can transport significant pollutant loads to streams and lakes.

SECTION 3 - GENERAL DESCRIPTION OF NSCS

The NSCS is both a biological filter and physiochemical treatment system. The goal of an NSCS is to maximize reduction of total and soluble phosphorus, and reduction of nitrogen, organic matter, bacteria and fine sediments reaching lakes and streams. The system is functional at different levels of efficiency during all seasons under a broad range of ecological, hydrologic and pollutant load conditions.

The complete NSCS (Figures 1 [Plan View] & 2 [Profile View] - See pages 3 and 4) shows a combination of a sediment basin, grassed buffer, a vegetated shallow pond, a deep pond, and a vegetated "polishing" area.

This particular hydrologic sequence is based on practical experience, typical site topography, soils, hydrology, economics, and the resulting effectiveness in reducing pollutants.

The components may be constructed together, as shown on the schematic in Figure 1, or modified to meet the site limitations. Figures 1 and 2 of the NSCS show numbered components. The size of each system and its individual components are based on a review of the literature of on-site research activities, hydrologic models (USDA, 1986), site conditions, and the degree of pollutant reduction anticipated (See Appendix - Table 1 - page 18). The NSCS size, criteria and procedures used for planning purposes are designed to be simple and will apply for most field conditions encountered by planning personnel.

The configuration of the components depicted in Figure 1 are presented for "informational and educational" purposes, which can be used when siting the NSCS. Every effort should be made to design the components so that their shape and appearance blends with the surrounding landscape. This includes construction materials such as stone, fencing, vegetation and other ancillary materials. An example of a site-sensitive design is shown in Figure 3 (See page 5).

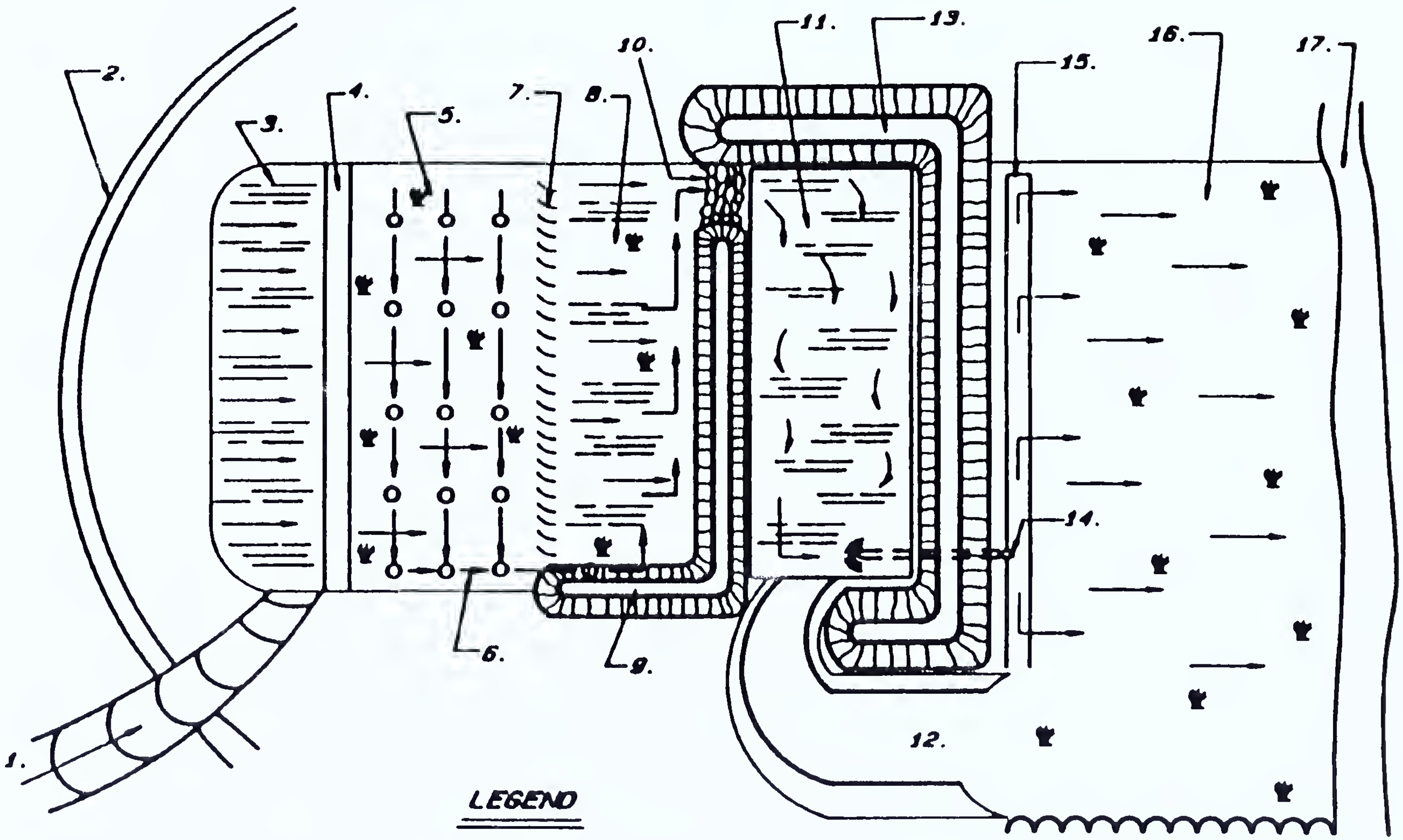
SECTION 4 - PLANNING AND SITE CONSIDERATIONS

In general, the system may reduce downstream peak discharges by storing some of the runoff. Flows and/or flow velocities from the contributing area may actually be increased if flow patterns concentrate water because of the placement of conservation practices, such as: diversions, grassed waterway, stripcropping, tillage patterns, etc.

This system is installed below cropland watersheds. The systems will be planned in accordance with Sections III and IV of the Field Office Technical Guide (FOTG). The soil and water conservation treatment within the contributing area shall be installed prior to planning an NSCS.

With the NSCS, evaporation and evapotranspiration are increased when compared to other pre-existing conditions. However, water in the system is conserved and is available for limited, specified, and

FIGURE 1 - PLAN VIEW

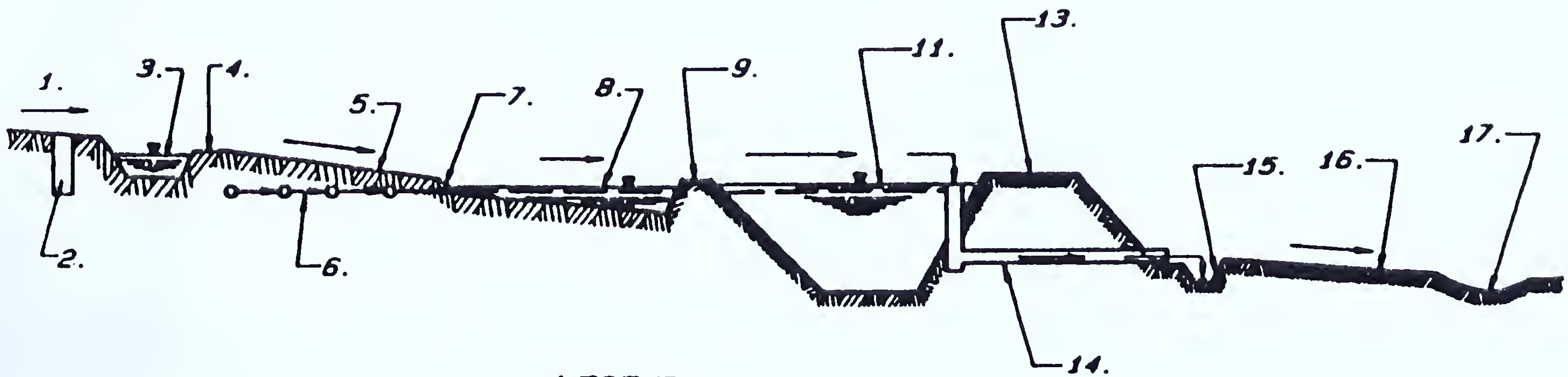


LEGEND

1. CONTRIBUTING AREA TO THE NSCS
2. CURTAIN DRAIN
3. SEDIMENT BASIN
4. LEVEL LIP SPREADER
5. GRASSED BUFFER
6. SUBSURFACE DRAINS
7. TRANSITION ZONE
8. VEGETATED SHALLOW POND
9. TRAINING DIKE
10. STABLE OUTLET
11. DEEP POND
12. VEGETATED EMERGENCY SPILLWAY
13. EMBANKMENT
14. PRINCIPAL SPILLWAY
15. DISTRIBUTION SPREADER
16. VEGETATED " POLISHING " AREA
17. STABLE OUTLET

NOT TO SCALE

FIGURE 2 - PROFILE VIEW

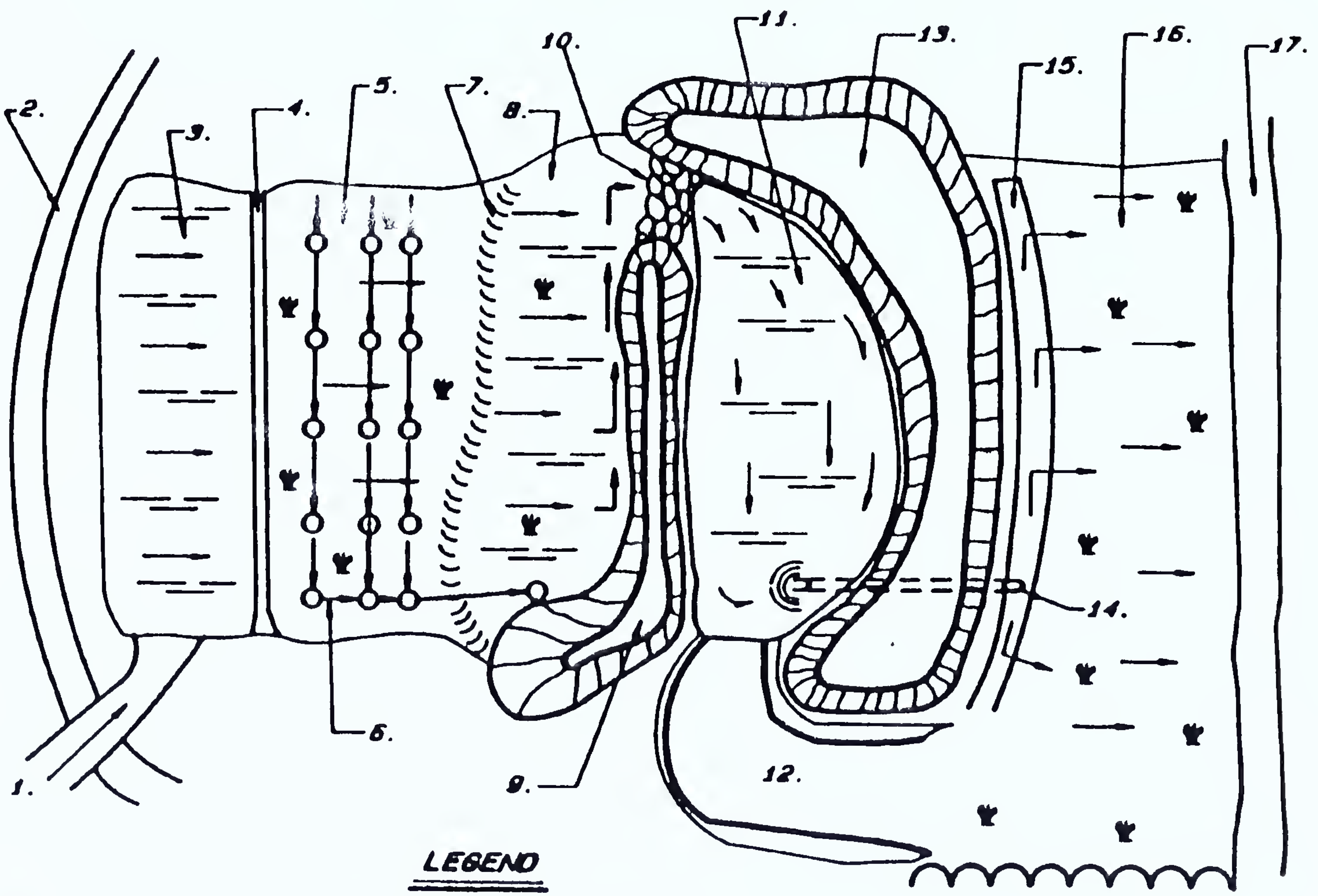


LEGEND

1. CONTRIBUTING AREA TO THE NSCS
2. CURTAIN DRAIN
3. SEDIMENT BASIN
4. LEVEL LIP SPREADER
5. GRASSED BUFFER
6. SUBSURFACE DRAINS
7. TRANSITION ZONE
8. VEGETATED SHALLOW POND
9. TRAINING DIKE
10. STABLE OUTLET (NOT SHOWN)
11. DEEP POND
12. VEGETATED EMERGENCY SPILLWAY (NOT SHOWN)
13. EMBANKMENT
14. PRINCIPAL SPILLWAY
15. DISTRIBUTION SPREADER
16. VEGETATED " POLISHING " AREA
17. STABLE OUTLET

NOT TO SCALE

FIGURE 3 – PLAN VIEW - SITE SENSITIVE DESIGN



LEGEND

1. CONTRIBUTING AREA TO THE NSCS
2. CURTAIN DRAIN
3. SEDIMENT BASIN
4. LEVEL LIP SPREADER
5. GRASSED BUFFER
6. SUBSUFACE DRIANS
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15. DISTRIBUTION SPREADER
16. VEGETATED " POLISHING " AREA
17. STABLE OUTLET

NOT TO SCALE

allowable uses, including waterfowl, fish and other biotic resources, fire protection and recreation.

Since NSCS's are usually located on ground water discharge areas, a site survey is needed to determine any degree of risk to the ground water.

Components of the system should be planned and designed to complement the visual and topographic resources of the area.

In some instances, mosquitoes may be of concern, but appropriate biological controls, proper construction and operation and maintenance can minimize the potential for a mosquito problem.

Appropriate consideration must be given to safety features, such as fencing, when the NSCS is located near residential areas.

An interdisciplinary approach must be taken to properly plan, locate, design and operate an NSCS.

Where possible, design the NSCS to avoid placement in valuable natural wetlands. The use of natural wetlands needs to be carefully assessed to prevent damage to valuable wetlands.

Federal, state and local laws, regulations and ordinances must be followed in the planning, design, construction, and operation and maintenance of the NSCS.

The life expectancy for an NSCS is estimated at 20 to 30 years, based on proper operation and maintenance and adequate conservation treatments in the contributing area.

The intended use of the NSCS is to function during runoff or storm events, which causes the greatest transport and delivery of pollutants. Pollutants will be reduced during all seasons, although seasonal variation will occur.

The temperature of runoff water may be warmed in the shallow and deep ponds under some conditions. The deep pond may serve to buffer water temperature changes if ground water cools the water in the ponds.

Generally, the water leaving the system will be well oxygenated due to aeration as the runoff water passes through the NSCS, plant photosynthesis, and removal of sediment and organic matter by the sediment basin, grassed buffer and vegetated shallow pond.

SECTION V - COMPONENT DESCRIPTIONS OF THE NSCS

5.1 Contributing Area to the NSCS (Number 1). The contributing area includes all land and associated conservation practices above the NSCS. These SCS practices may include: grassed waterways (412), terraces (600), dikes (356), diversions (362), contour farming (330), crop residue use (344), filter strip (393), cover and green manure crop (340), nutrient management (590) and pest management (595). These practices will reduce the loading of sediment and nutrients, which can effect the NSCS's efficiency.

The components of the NSCS are installed as needed to intercept surface and ground water flow. Runoff should be intercepted and directed to the sediment basin. Clean surface or ground water should be routed around the system, since it is relatively unpolluted and it may place an excess hydrologic loading on the NSCS.

Runoff from the contributing area will be passed through the NSCS. No bypass is needed or desirable because the largest storm events carry the most sediment and other pollutants. The NSCS can help reduce shock loadings of pesticides to the receiving water.

In Maine, monitoring over a three-year period showed that four to five significant rainfall events occurred between June and October, that delivered about 80-95 percent

of the annual phosphorous and sediment load.

On some sites, conditions may warrant the construction of a curtain drain to divert "clean" ground water around the NSCS. Excess ground water may reduce the effectiveness of the NSCS's.

5.2 Curtain Drain (Number 2). This is a drain which intercepts the path of subsurface water flow and diverts either all or a portion of same around the NSCS. As an option, it may be constructed using crushed stone to the depth of the subsurface flow with a permeable synthetic or natural filter material that prevents soil from clogging the crushed stone. Subsurface drains may also be installed within the crushed stone trench to facilitate the movement of subsurface water around the NSCS.

5.3 Sediment Basin (Number 3). The sediment basin is designed to collect large sediment particles and organic matter from runoff water prior to routing it through the treatment system. It provides pretreatment which protects the functions of the other components. It also serves to regulate flow, which minimizes excessive flushing of the ponds. The sediment basin buffers hydrologic flow and stores 100 percent of the water from small runoff events. This protects the ponds from frequent turbidity, which reduces biological activity and effectiveness of pollution control.

The sediment basin consists of a trapezoidal trench located across the slope. There is no pipe outlet. The bottom width should be a minimum of ten feet to facilitate cleaning with a front-end loader. Side slopes should not be steeper than two (horizontal) to one (vertical). It is important that the side slopes of this basin be vegetated to prevent erosion within the system. The length of the sediment basin should be at least equal to the width of the grassed buffer. Depth should be a minimum of four feet. Excavation should be to the most practical depth for the accommodation of maximum slopes and minimum dimensions. Side slopes should be adequately protected from scour.

A ramp should be provided on one end to provide access for sediment removal. The ramp should be no steeper than six (horizontal) to one (vertical) and is not to be included in the length of the basin. Protect the ramp during cleaning operations to reduce damage.

5.4 Grassed Buffer (includes the level-lip spreader, the subsurface drains and the transition zone).

5.4.1 Level-Lip Spreader (Number 4). This component insures the necessary sheet flow of water from the sediment basin to the grassed buffer. Sheet flow is insured by suitable vegetation type and stand density as well as good construction practice. The level-lip spreader must have a minimum berm width of eight feet. Within the berm, there shall be a four foot wide by one foot deep trench which is filled with crushed stone. The maximum crushed stone size is three inches and the minimum crushed stone size is one inch. Also, the crushed stone can resist adverse frost action. The crushed stone must be maintained level by hand raking as needed after the construction. Water flows into and over the crushed stone in the spreader then spreads evenly across it. Other suitable materials, such as pressure treated lumber or cedar logs, may be considered in place of crushed stone, where frost action is not a concern.

5.4.2 Grassed Buffer (Number 5). Grasses, which form sod and are capable of rapid growth during the cool moist periods of the year (cool season grasses), must be planted within this buffer. DO NOT USE REED CANARYGRASS because it competes with and will replace the cattails. The grassed buffer must be constructed with subsurface drains so infiltration can be increased and an aerobic root zone can be maintained. A filter fabric cover needs to be used to

minimize the effect of roots and soil upon the subsurface drainage system.

Divert stormwater flows around the grassed buffer when there is less than 80 percent permanent vegetative protective cover.

The grassed buffer also serves to protect the NSCS's aquatic plants and animals in the event of excessive pesticides, sediments and nutrients from surface runoff. In theory, it is easier to re-establish the grassed buffer than to re-establish the balances/equilibria that exist within the aquatic communities contained in the vegetated shallow and the deep ponds.

The grassed buffer area needs to be level from side-to-side (cross-slope) to provide a consistent sheet flow over the grassed buffer. The minimum and maximum slope from the influent end to effluent end needs to be five-hundredths feet per foot or five percent. For each increase in slope of one percent above the three-percent level, the length of grassed buffer is to be increased by 20 percent to maintain efficiency.

Three to four inches of topsoil needs to be spread over the grassed buffer area before planting of cool season grasses. Follow Soil Conservation Service establishment specifications for critical areas (SCS Practice Standard 342).

5.4.3 Subsurface Drains (Number 6). The grassed buffer must be constructed with a subsurface drainage system to:

1. Increase infiltration
2. Maintain the grass root zone in an aerobic condition
3. Prevent the area from being saturated for extended periods
4. Facilitate mowing and removal of grass

Space subsurface drain lines in accordance with the SCS drainage guide.

The subsurface drain should be no more than 15 feet downgradient from the level-lip spreader. The subsurface drain should outlet above the water surface of the vegetated shallow pond.

The subsurface drain must be at least four inches in diameter. Subsurface drain lines shall be installed according to SCS practice standard 606. A fabric guard and sand or bank run gravel filter shall be used to reduce the risk of roots and soil clogging the drainage lines. Drain lines usually outlet into the vegetated shallow pond, which is responsible for most of the nitrogen removal.

If nitrates are at acceptable levels, the subsurface drainage lines may outlet directly into the deep pond. If nitrogen levels are not elevated or if the subsurface drainage lines intercept ground water that is from other than grassed buffer infiltration, then diversion of this water around the vegetated shallow and deep ponds may be provided directly to a stable outlet. This will prevent excess clean water from flushing the NSCS by hydrologic loading. Refer to SCS practice standard 606 for more information.

5.4.4 Transition Area (Number 7). A transition zone may be necessary to insure uniform sheet flow to the vegetated shallow pond as well as to provide bank stabilization at the interface between the grassed buffer and the vegetated shallow pond. This transition zone may be protected with natural and/or synthetic materials. To date, the NSCS's installed have not needed such a transition zone.

5.5 Vegetated Shallow Pond (includes the vegetated shallow pond, the training dike and the stable outlet). The vegetated shallow pond is planted to emergent wetland plants and receives sheet flow and subsurface flow from the grassed buffer. The vegetated shallow pond maintains conditions suitable for a dense growth of

emergent aquatic vegetation. The depth of the vegetated shallow pond should range from saturated soil at the grassed buffer to one and one-half feet near the interface with the deep pond. The vegetated shallow pond should be planted to broad-leaf cattail (*Typha latifolia*) on an 18-to-24-inch spacing in staggered rows from the zone of saturation at the lower end of the grassed buffer to a water depth of 12 inches, depending on the size of the planting stock. Initially, cattails are used because they are easily established, exhibit rapid growth rates, are economical and are adapted to a wide range of site conditions. If salinity is greater than four mmhos/cm, use narrow-leaf cattail (*Typha angustifolia*) instead of broad-leaf cattail. During the life of the vegetated shallow pond, other species will become naturally established in or around the vegetated shallow and deep ponds, which will provide biodiversity.

In the event that criteria for the growth medium of the vegetation is of concern, the substrate shall be covered with four to six inches of topsoil, that is evenly spread on the subsoil surface prior to flooding and/or planting. Some other characteristics of the substrate to consider are as follows:

Other Substrate Characteristics:*

Salinity (mmhos/cm)	<4
pH	>3.6 & <8.5
Rock Fragments	
(<3 in. dia.) (weight percent)	<25
Fraction (>3 in. dia.) (weight percent)	<5
Available Water Capacity (in/in)	>0.10
Texture **	any textures except LOCOS, S, COS, LS, C, SIC, SC
Sodium Adsorption Ratio (SAR)	<13

* Source: Adapted from the USDA, SCS, National Soils Handbook, Table 603-20, dated July, 1983.

**These are ideal textures; however, nearly any texture is acceptable.

Other aquatic species may be used in the vegetated shallow pond in future applications as a result of research, where their suitability has been demonstrated. Commercially available plant sources are recommended unless locally available wild stock can be legally, conveniently and reasonably obtained for transplanting. Planting guidelines from the commercial suppliers should be followed except as noted below.

The vegetated shallow pond usually supports a combination of anaerobic and aerobic conditions in the soil and organic matter layer. These conditions are especially important in the removal of nitrates, ammonia and bacteria. This environment provides a suitable habitat for a dense growth of emergent aquatic vegetation and other micro- and macro-organisms.

Sago pondweed (*Potamogeton pectinatus*), a submerged aquatic plant, should be established where water depth exceeds 15 inches. Establish vegetation in the vegetated shallow pond in accordance with the following specifications:

5.5.1 Site Preparation. The vegetated shallow pond should be flooded to the proper depth (maximum of one and one-half feet) after topsoil is spread. The water level in the vegetated shallow pond is usually determined by the height of the primary spillway in the deep pond, unless the vegetated shallow pond is independent of the deep pond.

5.5.2 Season of Planting. The growing season will vary from location to location. Basically, the planting season will depend on local climatic conditions and the type of planting material, cuttings or seed being used. Commercial

sources will usually ship plants at the appropriate planting time as well as provide planting guidance.

5.5.3 Shallow Pond Vegetation. The cattail roots and shoots must be kept moist and cool from the time they are dug to the time they are planted. Sago pondweed must be kept completely saturated with water from the time of harvest to the time it is planted. Temporary storage should not exceed three days and be at a temperature between 35 and 40 degrees Fahrenheit.

5.5.4 Training Dike (Number 9). A training dike should be located between the vegetated shallow pond and the deep pond to avoid short circuit flow. The minimum design criteria should be as follows:

minimum berm width	4'-0"
minimum side slopes (horizontal to vertical)	2:1
maximum side water depth	1'-6"
minimum freeboard depth	1'-0"

A training dike may not be needed if the flow path through the shallow and deep ponds are elongated due to site conditions.

5.5.5 Stable Outlet Area (Number 10). The vegetated shallow pond shall have a stable outlet constructed of rock riprap. The stable outlet should be at the point farthest from the principal spillway and the emergency spillway of the deep pond to create a long flow path. The outlet will be needed when a training dike has been provided. The purpose of the outlet is to provide a stable interface between the vegetated shallow pond and the deep pond. The minimum bottom width of the stable outlet shall be six feet.

5.6 Deep Pond (includes a number of biological and physical elements) (Number 11). This is the most important component of the NSCS, even though it may not function effectively by itself. The deep pond is created by impounding or by impounding and excavating to obtain the required depth and size. The pond should have a maximum depth ranging from seven to twelve feet. Establishment of plants and animals within this component is required. A biologically viable ecosystem needs to be established in the shallow and deep ponds for the NSCS to function consistently and at optimum effectiveness. Many pollutants are transformed into biomass through the food chain and are eventually converted into organic materials or removed from the system. This is not only a significant part of the pollution removal process but also provides other environmental, economic and social values.

5.6.1 Baitfish (minnows). The conversion of nutrients to fish flesh is accomplished by food chain factors of fish consuming micro- and macro-invertebrates, algae and plankton. Fish are very efficient converters of food to biomass. Fish species selection is based on their food requirements, reproductive requirements and other economic values.

Golden shiners (*Notemigonus crysoleucas*), fathead minnows (*Pimephales promelas*) and lake chubsuckers (*Erimyzon sucetta*), are recommended species that can survive and reproduce in these ponds. Cyprinids (minnows) are typically chosen because their food requirements result in removal of nutrients during all seasons of the year. However, during winter conversions are reduced due to reduced biological activity.

In addition, the fish will also feed on insect larvae helping keep the mosquito population to a minimum. The fish can also serve as indicators of toxic levels of pollutants.

5.6.2 Stocking Rate For Baitfish. Stocking should be accomplished with a minimum of 20 pounds of three to four inch "baitfish" per 10,000 square feet of pond surface area. A variety of appropriate species may be used. The fish will also populate the vegetated shallow pond. Fish should be obtained from wholesale baitfish suppliers. State fish stocking regulations must be followed. Bottom feeders, such as carp (*Cyprinus carpio*) and catfish or bullheads (Ictaluridae family) are not suitable. These fish cause excessive water turbidity, due to their feeding behavior. This turbidity affects biological activity within the pond, reduces pollutant removal efficiency and can be harmful to mussel or clam populations.

Local trapping of baitfish is an alternative; however, it is very time consuming and quality control is not as good.

5.6.3 Fresh Water Mussels or Clams. Fresh water mussels or clams are common in most lakes and rivers in North America. They live on the bottoms of rivers and ponds. Mussels and clams are natural "filter" feeders that are able to tolerate considerable amounts of nutrient pollution, turbidity, temperature variations and low dissolved oxygen.

They are called "filter" feeders because they pump water through their digestive tracts and remove algae, plankton, other organisms and suspended organic matter for nourishment and expel cleaner water. The mussels or clams convert this food to flesh and energy and their waste products are minimal.

Each mussel or clam "filters" one and one-half to two tablespoons of bottom water per minute which results in 10 to 12 gallons of water per day. Mussels and clams only stop feeding when disturbed or during periods of high sediment concentration. Therefore, 500 adult mussels possess the ability to "process" about 5,000 gallons of water per day. This is significant, especially when compounded with the effects of other invertebrates (Daphnia, etc) that also filter large quantities of water.

Some mortality of mussels or clams will occur. Raccoons, muskrats and other animals feed on mussels. This is part of the food chain nutrient removal process. However, the goal is to establish a reproducing population. Aquatic chemicals such as herbicides should be excluded from the pond. If natural reproduction of mussels or clams is inadequate, the pond may require restocking every three to five years.

5.6.4 Stocking Rates For Mussels or Clams. Stocking should be at a rate of approximately 500 adult (two and one-half inches or larger) mussels or clams per 10,000 square feet of pond surface area. Mussels should be placed into the permanently flooded areas of the pond. Stocking should be accomplished one year after normal water level is established.

Mussels or clams should be collected by trained personnel or purchased through biological supply sources. Mussels should be stocked within 48 to 72 hours after being collected. Mussels or clams should be chilled and aerated when in temporary storage before stocking. Applicable federal, state and local laws shall be observed when collecting and/or stocking mussels. An aquatic biologist should be consulted to preclude the collection of undesirable or endangered species of mussels or clams.

5.6.5 Other Species. It is usually unnecessary to stock frogs and other aquatic organisms because they will quickly colonize the sites from other nearby locations. Frogs are effective, seasonal, biological transformers of nutrients through the food chain. Where NSCS's are isolated from other wetlands and bodies of water, it may be desirable

to stock species, such as frogs. An aquatic biologist should be consulted concerning needs and feasibility.

Inoculation of "pond water" with micro-organisms is usually unnecessary; however, it can aid in the colonization of isolated pond systems by micro-organisms through the addition of an initial source of plankton. An aquatic biologist should be consulted regarding a viable source and amount of innoculant water.

5.6.6 Plants in the Deep Pond. The majority of the area of the deep pond will be free of aquatic vegetation. Aquatic plants that form submerged, net-like growths are planted in the deep pond. Sago pondweed (*Potamogeton pectinatus*) has been used successfully. These plants should be planted one growing season after the completion of construction. Sago pondweed and other plants will be limited by the depth and transparency of the water.

The perimeter of the pond will develop a fringe of cattails and other emergent plant growth. However, if the side slopes of the pond are two (horizontal) to one (vertical), the width of this fringe will be narrow.

5.6.7 Vegetated Emergency Spillway (Number 12). This consists of a vegetated earthen channel, usually designed to discharge flow in excess of the principal spillway design discharge. emergency spillway should be included into the design to preclude concentrated flow and to promote sheet flow. Routing of the two-to-five-year, 24-hour storms through the principal spillway is needed to set the riser crest and level of the emergency spillway. The greater the storage capacity of the vegetated shallow and deep ponds, the greater the efficiency of the NSCS.

The emergency spillway must safely pass flows in excess of the design storm and provide additional vegetative buffer to reduce the suspended solids during peak runoff periods. The spillway should not be installed on a slope greater than eight percent. This vegetated emergency spillway may also provide some treatment as design stormwater flows through the system during the growing season. The following criteria are recommended:

1. Locate the principal and emergency spillways on the same side of the deep pond.

2. The principal and emergency spillways need to be on the opposite side of the deep pond from where the shallow pond enters whenever possible to provide the longest flow path.

For more detailed information refer to the SCS Engineering Field Manual, Chapter 11, as last revised and the SCS Technical Release Number 2, as last revised.

5.6.8 Embankment (Number 13). The interior slopes should be no flatter than two and one-half (horizontal) to one (vertical), if possible. Under certain circumstances, a two (horizontal) to one (vertical) slope may be preferred to provide for increased pond volume capacity and less land area utilization. The embankment criteria should be as prescribed in Chapter 11 of the SCS Engineering Field Manual as last revised. Also, refer to SCS Pond Practice Standard 378.

5.6.9 Principal Spillway (Number 14). The principal spillway should be constructed of permanent material. The design needs to provide for the reduction in the frequency of operations of the emergency spillway. The principle spillway discharge capacity depends upon the hydraulic sizing of the ponds. It should be used for retarding peak flows, discharge a low percentage of the peak flow and act in flow regulation and hydraulic detention for treatment of pollutants. There should be sufficient storage capacity in the NSCS to minimize flow through the principal spillway.

The deep pond should be designed with a drop-inlet pipe spillway that includes a drain for maintenance. This type spillway will provide aeration of the water as it is discharged from the deep pond. Also, refer to SCS Pond Practice Standard 378 for detailed design information.

5.7 Vegetative "Polishing" Area (optional) (includes a distribution spreader, a vegetated "polishing" filter and a stable outlet) (Number 16). This area, which is downgradient of the deep pond, consists of a stable, relatively level, vegetated site. Sheet flow will be required to preclude gullying and short-circuiting of flow. The area may be grassland, wetland, riparian area, or forested area, either natural or constructed between the distribution spreader and a stable outlet at the receiving water body.

The "polishing" area serves as a final buffer between the NSCS and the receiving water body. The area helps to remove residual algae and other matter from the pond effluent.

If the "polishing" area is constructed, the vegetation should consist primarily of sod-forming cool-season grasses. Duplication of the grassed buffer (Number 5) at this point would be ideal but site conditions may not allow this. A subsurface drainage system is not necessary.

It is difficult to construct or modify suitable "polishing" areas. All monitoring data to date has been obtained without the benefit of a "polishing" area.

Natural vegetation should be used, if available. Concentrated flow should be minimized with the use of the distribution spreader and natural vegetation. If the emergency spillway outlets directly into this area, consideration must be given in the design for sheet flow to prevent gullying.

5.7.1 Distribution Spreader (Number 15). Use of a plunge pool at the end of the principal spillway pipe may be needed. This is created by installing a stone check dam in the side of the plunge pool to allow low flows to seep through the stone and onto the vegetated area.

A distribution spreader should be provided to uniformly distribute flow from the principal spillway outletting to a vegetated "polishing" area. A level spreader ditch followed by a level-lip spreader may need to be provided, so uniform flow distribution through the vegetated "polishing" area is facilitated. The minimum design criteria for the distribution spreader includes:

minimum top width	3.0 feet
minimum side water depth	1.5 feet
minimum freeboard depth	1.0 feet

5.7.2 Stable Outlet. A stable outlet is a structure or channel that is protected from excessive scour. It is used to control the discharge of water. SCS practices that provide information on stable outlets include: rock-lined waterway or outlet (468) and grassed waterways (412). Existing natural channels with stable sides and bottoms may be suitable.

SECTION 6 - WHEN CHANGES TO COMPONENT SIZE SHOULD BE MADE:

When the size of a component is limited due to site conditions, the size of the deep pond and sediment basin should be increased and the size of the vegetated shallow pond and grassed buffer should be decreased to the next lower size as described in Appendix Table 1.

When nitrates, ammonia, biochemical oxygen demand, and fine sediments are overriding concerns and phosphorus is not the primary concern, the vegetated shallow pond should be increased (at least doubled) in total size. The size of the deep pond may then be decreased proportionately, but not eliminated from the NSCS.

There may be cases where the size of the grassed buffer, vegetated shallow pond, deep pond, or vegetated "polishing" area is reduced due to unavoidable site limitations. In such cases, the sediment basin should be increased to the next larger size as shown in Appendix Table 1. If the area is limited, the sediment storage may be increased to the greatest extent practical by increasing the sediment basin depth. This will help to compensate for the change in system effectiveness due to site constraints.

SECTION 7 - NSCS CONSTRUCTION COST

To date, actual NSCS construction costs in Maine have ranged from $14,000 to $35,000 per system depending on site conditions.

Costs should be amortized over a 25-year life expectancy and related to the number of acres of "treated" contributing area.

Amortized construction costs in Maine have ranged from $17 to $22 per acre of contributing area each year.

The 25-year life expectancy is based on the pipe used in the principal spillway. With proper design, maintenance and land treatment in the contributing area, the NSCS's useful life may be substantially longer.

SECTION 8 - OPERATION AND MAINTENANCE

8.1 General. Implementation of the operation and maintenance plan is essential to ensure efficient operation for each NSCS installed.

8.2 Sediment Basin (Number 3). Clean out the sediment basin when the accumulated sediment reaches a depth of 12 inches. This is essential to prevent overflow of sediment onto the grassed buffer and into the ponds. The sediment removed should be deposited on the land away from the NSCS in an environmentally sound manner that will minimize erosion and subsequent deposition in the receiving water bodies.

Excessive sediment will reduce the efficiency of the NSCS. As sediment accumulates and overflows into other components, concentrated flow and erosion of the grassed buffer can occur.

Excessive sedimentation and turbidity reaching the ponds will reduce biological and chemical assimilative capacity. Pollutant control processes would be adversely impacted. This concentrated flow can even result in a reduced detention time for heavy sediment removal.

Removal of plant growth in this basin is not necessary.

8.3 Grassed Buffer (includes level-lip spreader, subsurface drain and transition zone.)

8.3.1 Level-Lip Spreader (Number 4). Maintain by raking or grading, as needed, to promote sheet flow onto the grassed buffer. This is especially important during the first three years of operation or until the NSCS is well established. Eventually, sediment will fill the voids in the stone and vegetation will grow in the spreader. The spreader should be maintained free of brush and trees. Failure to do so will cause flow to concentrate and render it ineffective.

8.3.2 Grassed Buffer (Number 5). The buffer should be mowed at least twice during the growing season to a three-inch height and the clippings removed to maintain a dense vigorous sod. Harvesting should occur between June 25 and July 5 and between September 1 through 30 or at times appropriate to the particular climatic region. Mowing before June 25 may destroy waterfowl nests. At the end of the growing season, the grass should be

at least four inches high. The vegetation that is removed may be used as mulch, forage, bedding, compost or transported out of the drainage area for other uses. Regrading, reseeding, and fertilizing shall be done as needed to maintain the effectiveness of the grassed buffer.

8.3.3 Subsurface Drain (Number 6).

Subsurface drains under the grassed buffer must be maintained in a free flowing condition. At the subsurface drain outlet, the rodent guard must be maintained. Also, algae and root hairs must be removed from the rodent guard to prevent clogging.

8.4 Vegetated Shallow Pond (Number 8).

Harvesting cattails is unnecessary and may harm the detritus/humus layers of the vegetated shallow pond. Also, harvesting can reduce the plant's ability to transfer oxygen to the roots.

8.5 Deep Pond (Number 11).

Remove any dense floating mats of filamentous algae by raking. This material should be taken to upland sites for disposal. One method of disposal is composting.

Maintenance of embankment vegetation needs to be performed to preclude bank erosion and control brush and other unwanted vegetation. Mow the embankments and the emergency spillway as necessary to maintain a dense stand of vegetation and control trees, shrubs or other undesirable vegetation.

Trash should be kept from accumulating in the principal spillway. Inspections for seepage through the embankment should be checked on a regular basis.

Restocking of fish and mussels or clams may be needed periodically and should be evaluated by an aquatic biologist. Fish should be restocked in the spring in the event of winter die-off. Harvesting of fish is a necessary maintenance practice and should be incorporated into the plan. No supplemental feeding of fish needs to be conducted. No chemical treatment needs to be used in the pond unless recommended by an aquatic biologist. Commercial fish harvesting is desirable (baitfish for sport fishing). Harvesting of fish will remove nutrients from the deep pond. Nutrients sequestered in the bodies of the fish are removed with harvesting. This is especially desirable during the fall and early winter, but may be done throughout the growing season. Predation by mammals and birds will help remove nutrients from the system.

If nutrient loads cause advanced eutrophication or extended anaerobic conditions, aeration or other destratification techniques may be necessary. However, prior to any remedial activity, an aquatic biologist, or an environmental engineer should be consulted.

8.6 Vegetated "Polishing" Area (Number 16).

The "polishing" area must be maintained to avoid concentrated flow. Manage vegetation to maintain a dense, vigorous vegetative "filter."

8.7 System Effectiveness Monitoring.

The NSCS is a complex system involving many physical, chemical, and biological processes. Monitoring of the effectiveness is complicated. Some recommended guidelines for monitoring are presented below:

1. Physical measurement of sediment accumulation in the sediment basin with a calibrated pole.

2. Measurement of water chemistry at the influent and effluent ends of the NSCS through the use of a system that is initiated with storm events. Some of the parameters that may be considered include:

Nitrate-nitrogen
Total phosphorus
Turbidity
Suspended Solids
Ammonia-Nitrogen

3. Measurement of inflow and outflow on a storm event basis.

4. Analysis of total annual flows and loadings through the NSCS related to amounts of precipitation.

5. Measurement of chlorophyll "a" concentrations in both the vegetated shallow pond and the deep pond.

6. Analysis of the vegetated indigenous and non-indigenous biotic communities for dominance, species diversity, age, structure, reproduction and other related studies that measure their health and vigor.

7. Pond monitoring parameters such as temperature, dissolved oxygen, carbon dioxide, pH, nitrogen, phosphorus, methane, hydrogen sulfide and other related water quality indicators can be useful in evaluating NSCS performance.

8. Plant tissue studies to determine the uptake of nutrients by aquatic and terrestrial vegetation.

9. Consideration may be given to long-term monitoring of the ground water around the NSCS.

8.8 NSCS Operation and Maintenance Costs.

Operation and maintenance costs include mowing, trash removal, brush control, fish harvesting, filamentous algae mats, and other vegetation removal and sediment clean out.

Maintenance costs in Maine average about $50 per year per system.

SECTION 9. REFERENCES

Bouchard, Roy. 1990. Pers. Comm. and unpublished monitoring reports. Maine Dept. of Environmental Protection, Lakes Division, Augusta, ME.

Cooper, Paul F., 1990. (ED.) "Use of Constructed Wetlands in Water Pollution Control." Water Research Center, Buckinghamshire, SL7 2HD, England.

Dickerman, Joyce, A., A.J. Stewart, and C.J. Lance, 1985. "The Impacts of Wetlands on the Movement of Water and Nonpoint Pollutants from Agricultural Watersheds." USDA-ARS - Water Quality and Watershed Research Laboratory, Durant,OK.

Godfrey P., E.R. Kaynor, S. Pelczarski, J. Benfordo, 1985. "Ecological Considerations in Wetlands Treatment of Municipal Wastewater." Van Nostrand Reinhold Company, New York, NY, pp 7-25, 137-157.

Hammer, D. A., B. P. Pullin and J. T. Watston, 1989. "Constructed Wetlands for Livestock Waste Treatment." Proc. Nat'l Nonpoint Conference, St. Louis, MO, April 23-26, 1989.

Hammer, D.A. 1989. "Constructed Wetlands for Treatment of Agricultural Waste and Urban Stormwater." In S.K. Majumdar et. al. (eds) Wetlands Ecology and Conservation: Emphasis in Pennsylvania. The Pennsylvania Academy of Science.

Hammer, Donald A. 1989. (Ed.) "Constructed Wetlands for Wastewater Treatment: Municipal, Industrial, Agricultural," (Proceedings from the First International Conference on Constructed Wetlands for Waste Treatment), Lewis Publishers, Inc. Chelsea, MI. 831 p.

Hammer, Donald A., "Creating Freshwater Wetlands." Lewis Publishers, Boca Raton, FL 1992.

Jolly, James W., 1990. "The Efficiency of Constructed Wetlands in Reduction of Phosphorus and Sediment Discharges from Agricultural Watersheds." Unpublished M.S. Thesis, University of Maine, Orono, ME.

Maddox, J. J. and J. B. Kinglsey, 1989. "Waste Treatment for Confined Swine with an Integrated Artificial Wetland and Aquaculture System." In D. A. Hammer (ed.) Constructed Wetlands for Wastewater Treatment. Lewis Publishers, Inc. Chelsea, MI. 831 p.

Maryland Department of Natural Resources, 1987. Sediment and Stormwater Division, Water Resources Administration, "Guidelines for Constructing Wetland Stormwater Basins."

Mitch, William J. and J.G. Groselink, "Wetlands." Van Nostrand Reinhold Company, New York, NY, 1986. pp 3-13, 55-125.

Reddy, K. R. and W. F. DeBusk, 1985. "Nutrient Removal Potential of Selected Aquatic Macrophytes." Journal of Environmental Quality, Volume 14, October-December, Number, pp 459-462.

Reddy K. R. and W. H. Smith (Editors), 1987. "Aquatic Plants for Water and Resource Recovery." Magnolia Publishing, Orlando, FL. 1032 p.

Reed, S.C., D.J. Middlebrooks and R. W. Crites, 1988. "Natural Systems for Waste Management & Treatment." McGraw-Hill, NY 291. p.

Reed, Sherwood C., 1990. (ed.) "Natural Systems for Wastewater Treatment Manual of Practice FD-16." Water Pollution Control Federation, Alexandria, VA. 270 p.

USDA, Soil Conservation Service, 1986. "Urban Hydrology for Small Watersheds, Technical Release No. 55." USDA SCS Engineering Division, Washington, DC.

United States Patent Office, Wengrzynek, Robert J. Jr. (Inventor) and USDA Secretary of Agriculture (Assignee), US Patent Number 5,174,897, "Constructed Wetlands to Control Nonpoint Source Pollution," December 29, 1992.

Walker, William W. Jr., 1986. "Phosphorus Removal by Urban Detention Basins," in Proceedings of 6th Annual Symposium, North American Lake Management Society (NALMS), Portland, OR.

Wengrzynek, Robert J. Jr., 1990. "Unpublished Reports and Draft Interim Standards and Specifications (Code I-05) Nutrient/Sediment Control Systems." USDA Soil Conservation Service, Orono, ME.

Wengrzynek, Robert J., Jr., Biologist and Terrell, Charles R, National Water Quality Specialist, USDA, SCS, "Using Constructed Wetlands to Control Agricultural Nonpoint Source Pollution." International Conference on the Use of Constructed Wetlands in Water Pollution Control at Churchill College, Cambridge, United Kingdom, September, 24-28, 1990.

SECTION 10 . APPENDIX

10.1 Table 1 (Page 18) describes the minimum size criteria for an NSCS for agricultural land, cropland, hayland and pastureland with average slope to 8 percent (potato, corn, or other row crop).

10.2 Notes Relating to Table 1

Table 1 was prepared based on field experience and best practical judgement of biological systems.

Values described in Table 1 were developed in cooperation between the SCS Maine State Office and the Maine Department of Environmental Protection. Numbers represent estimates based on

TABLE 1 PRACTICE COMPONENTS							
CONT. AREA (AC)	SED. BASIN (SQ FT)	GRASSED (SQ FT)	BUFFER (FT)	VEGETATED SHALLOW POND (SQ FT)	DEEP POND (SQ FT)	VEGETATED "POLISHING" AREA (SQ FT) GRASSED	(SQ FT) WOODED
<25	1,000	10,000	100	10,000	10,000	3,750	7,500
50	1,250	12,500	125	12,500	16,000	5,000	10,000
75	1,500	15,000	150	15,000	22,000	6,250	12,500
100	2,000	17,500	175	17,500	28,000	7,500	15,000
150	3,000	22,500	225	22,500	40,000	10,000	20,000

\>150 acres - Increase size of components proportional to contributing area

experience and knowledge of these agencies involved.

Interpolate for other contributing areas and then size the components proportionally or, to increase effectiveness, use the next larger size. Some additional criteria and assumptions includes:

1. These criteria are minimums to use if the site conditions permit. Larger sizes should be used where possible, for greater flow-through or detention time if cost effective. Smaller sizes are feasible at reduced treatment efficiency if construction is hydrologically stable.

2. The criteria assume that soil loss and other contaminants in the watershed are reduced to "T" or lower levels as applicable. Increase sediment basin size proportional to soil losses above

3. Size of deep pond should increase 50-100 percent if phosphorus loads are exceptionally high or continuous. This size increase should be made proportionately by surface area. Pond depths greater than 10 feet are discouraged to keep the NSCS cost-effective.

4. The contributing area size is based on the area in agricultural cropland assuming that "clean water" has been excluded from the system, as far as practical.

5. For every 2 percent increase in slope the size of each component should be increased approximately by 10 percent. This will allow for greater detention time for treatment in the NSCS on steeper slopes. On slopes greater than 8 percent, cost-effectiveness becomes critical.

6. For contributing areas greater than 150 acres, the sizes should be increased in direct proportion to those given for the 150-acre category.

7. Hydraulic loading is only one factor among many that should be considered in determining the size of the NSCS.

8. Also, sizing should consider pollutant loading and the detention time necessary to assimilate loadings from the contributing area.

10.3 Some Specialized Installation Procedures

1. Do not bypass this system during major runoff events. These events usually carry the greatest pollutant loads.

2. Install necessary water control measures to exclude excessive clean runoff water from the system. An erosion and sediment control plan should be followed throughout the construction period of the NSCS.

3. The erosion control devices and/or any temporary debris basin shall be removed after permanent vegetative cover has been established over 90 percent of the area disturbed by construction.

4. Runoff water should be diverted through the sediment basin or other temporary debris basin and then bypass the system until the grassed buffer becomes established.

10.4 Design Equation Guidance

1. The NSCS design may be developed using the following:

   a. For Stormwater Flows from the Contributing Area:

      SCS TR-55
      SCS TR-20

   b. For the Sedimentation Basin:

      Newton's and Stoke's laws

   c. For the level-lip spreaders and the spillways:

      Weir and spillway models

   d. For the grassed buffer:

      Manning's and Darcy's equations

   e. For the Shallow and Deep Ponds:

      SCS Pond Practice - Standard 378
      Iowa Ponds Program

   f. For the Vegetated "Polishing" Area:

      Riparian Forest Buffer Criteria (USDA - Forest Service, Northeastern Area, Radnor, PA)

APPENDIX D

TABLE 3, BASE CASE SOLUTION
NUTRIENT REDUCTION COST EFFECTIVENESS ANALYSES
SRBC Publication No. 161

TABLE 3. Base Scenario, Susquehanna River Basin Strategy Summary

Minimum Cost - 1985 TN,TP Effluents

	1985 Controllable Load		Target Load		Adjusted Target Reduction*	
	Nitrogen	Phosphorus	Nitrogen	Phosphorus	Nitrogen	Phosphorus
Point	10,655	1,475				
Nonpoint	35,329	3,972				
Total	45,984	5,447	27,590	3,268	19,499	2,118

* Reflects changes in nonpoint nutrient loads associated with use of year 2000 land uses

Nonpoint Sources

Landuse	BMP	Acres Treated (thousands)	1985 Load of Treated Acres Nitrogen	1985 Load of Treated Acres Phosphorus	Post-BMP Load Nitrogen	Post-BMP Load Phosphorus	Reduction Nitrogen	Reduction Phosphorus	Annual Cost (thousands)
Conv Tillage	Cons Till(CT)	0	0	0	0	0	0	0	$0
	Nut Mgmt (NM)	0	0	0	0	0	0	0	$0
	Farm Plan(FP)	0	0	0	0	0	0	0	$0
	HEL Conv	117	3,237	199	1,139	19	2,098	180	$15,172
	Cons Till+NM	0	0	0	0	0	0	0	$0
	Cons Till+FP	0	0	0	0	0	0	0	$0
	NM+FP	267	5,449	167	3,936	116	1,513	51	$2,569
	CT+NM+FP	529	13,426	783	9,308	467	4,118	316	$17,817
Cons Tillage	Nut Mgmt (NM)	29	328	9	306	6	22	3	$69
	Farm Plan(FP)	0	0	0	0	0	0	0	$0
	HEL Cons	105	2,368	151	1,072	21	1,296	130	$13,635
	NM+FP	524	11,480	612	9,756	493	1,724	119	$8,569
Hay Acres	Nut Mgmt (NM)	666	5,877	408	5,372	349	505	59	$1,598
	Farm Plan(FP)	0	0	0	0	0	0	0	$0
	HEL Hay	0	0	0	0	0	0	0	$0
	NM+FP	541	6,351	257	3,320	129	3,031	128	$5,051
Pasture	Farm Plan(FP)	911	7,868	88	6,294	76	1,574	12	$9,758
Manure	An Waste	1	1,221	185	305	46	916	139	$20,923
Urban	Low Density	0	0	0	0	0	0	0	$0
	High Density	0	0	0	0	0	0	0	$0
Forest	For BMP	64	170	1	(254)	(5)	424	6	$3,265
TOTALS		3,754	57,775	2,860	40,554	1,717	17,221	1,143	$98,426

Point Sources

	Retrofit Option	Number of Plants Retrofit	1985 Load Nitrogen	1985 Load Phosphorus	Post-Retrofit Load Nitrogen	Post-Retrofit Load Phosphorus	Reduction Nitrogen	Reduction Phosphorus	Annual Cost (thousands)
Point Sources	No Retrofit	18	824	124	344	15	480	109	$0
	TN=12, TP=1.5	7	387	48	298	23	89	25	$4,530
	TN=8, TP=1.5	28	4,751	543	2,441	242	2,310	301	$27,914
	TN=8, TP=0.5	0	0	0	0	0	0	0	$0
	TN=3, TP=0.5	0	0	0	0	0	0	0	$0
	TN=3, TP=0.1	5	540	135	240	4	300	131	$10,153
	TP=2 mg/l	4	90	23	86	4	4	19	$514
	TP=1 mg/l	77	4,064	602	4,967	210	(903)	392	$3,452
	TOTALS		10,656	1,475	8,376	498	2,280	977	$46,563

Note: Loads and reductions in thousands of pounds per year

TOTALS: NPS + PS:	19,501	2,120	$144,989

SUSQUEHANNA RIVER BASIN COMMISSION

DEC. 24, 1970

N.Y.

PA.

MD.

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